Research Expo

2013

HERRICK LABORATORIES
PURDUE UNIVERSITY™

GROUP A - THERMAL SCIENCES

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GROUP D - ELECTROMECHANICAL SYSTEMS/CONTROLS & VIBRATIONS

APPLICATION OF OIL FLOODED COMPRESSION WITH REGENERATION TO A PACKAGED HEAT PUMP SYSTEM

Research Assistants: Bin Yang, Tim Blatchley, Christian Bach

Principal Investigator: Professors James Braun, Eckhard Groll and Travis Horton

ABSTRACT

The heating capacity and coefficient of performance (COP) of conventional air-source heat pumps decreases towards lower ambient temperatures. Additionally, the heat pump stops running at very low ambient temperatures due to the high discharge temperature at the outlet of the compressor.

Oil injected into the compression chamber absorbs the heat generated during the compression process and thus, reduces the compressor discharge temperature. This allows the application of air-source heat pumps in regions of low ambient temperatures during the winter month. In addition, the compressor power consumption decreases with oil injection. Furthermore, the system performance of a vapor compression system with oil flooded compression can be significantly improved when also using a regenerative heat exchanger.

The work presented on this poster shows the simulation results applying the oil flooded compression with regeneration technology to a vapor compression cycle with a secondary loop for providing the required heating load. In addition, experimental results of a R410A 5-ton small packaged heat pump, which was retrofitted with an oil injected compressor and regenerator, are presented.

Compared to the performance of the secondary loop baseline cycle without oil injection, the system COP increases by more than 13% at an ambient temperature of -30 ^{o}C when liquid flooding and regeneration is used. The testing of the 5-ton small packaged heat pump modified for use with the oil injection and regeneration technology showed a system COP improvement of more than 7%. Additionally, a higher superheat at the compressor suction leads to larger improvement of the system COP if the ambient temperature stays constant.

COLD CLIMATE HEAT PUMP USING VAPOR INJECTED COMPRESSION

Research Assistants: Christian Bach, Bernhard Vetsch

Principal Investigator: Professors James Braun, Eckhard Groll and Travis Horton

Sponsor: U.S. Department of Energy

ABSTRACT

Building heating requirements increase with decreasing ambient temperature, while the coefficient of performance of air-source heat pumps shows the opposite trend. Additionally, heating capacity decreases with ambient temperature, which leads to the utilization of inefficient electric reheat.

Increasing the capacity and COP at lower ambient temperatures is therefore essential, especially for cold climates. Simulation studies previously showed that compressor vapor injection leads to an increase of COP under exactly those conditions. Furthermore, a reduced capacity degradation towards smaller ambient temperatures was predicted.

The work presented on this poster shows experimental results obtained from a commercially available 5-ton heat pump that was retrofitted with a dual port vapor injected compressor. With identical compressor speed, a 28% improvement in capacity can be achieved at the -8.33°C (47 F) design point, when compared to the baseline without vapor injection. If baseline and vapor injected system capacity are matched by adjusting compressor speed, the COP is increased by more than 6%.

A bin-type analysis of the experimental data predicts an improvement in HSPF of 6% for Minneapolis and nearly 7% for ASHRAE climate region 5.

SECONDARY LOOP AIR CONDITIONER FOR RESIDENTIAL APPLICATIONS USING PROPANE

Research Assistants: Tim Blatchley

Principal Investigator: Professors James Braun, Eckhard Groll and Travis Horton

Sponsor: Carrier Corporation, Emerson Climate Technologies, Grundfos

ABSTRACT

The development of secondary loop systems for residential applications is motivated by a desire to use natural refrigerants which have good thermodynamic and thermophysical properties in the primary vapor compression portion of the system, but cannot be used in conventional air conditioners due to their flammability and/or toxicity. Natural refrigerants are also desirable because of their low global warming potentials which will allow them to escape future refrigerant phase-outs. Secondary loops allow natural refrigerants to be used since they never enter the conditioned space. However, due to the addition of an intermediate heat exchanger the secondary loop system may have greater cost and potentially lower performance than traditional direct expansion (DX) split systems. Another disadvantage of secondary loop systems that utilize hydrocarbons as the primary refrigerant is the current regulations limiting the charge of flammable refrigerants permitted in residential systems. However, with the use of brazed plate heat exchangers the charge can be drastically reduced from a standard DX system. Despite these disadvantages, modeling has shown that a secondary loop air conditioner may outperform a traditional DX system since the primary refrigerant and secondary fluid have advantageous properties. System level cost and performance optimization were done to design a prototype secondary loop system to determine how competitive these systems will be compared to traditional DX systems on the market today.

Innovative Oil-Free Compressor and Expander Technologies

Research Assistants: Domenique R. Lumpkin

Principal Investigator: Professor Eckhard Groll

Sponsor: S-RAM Dynamics

ABSTRACT

The Herrick Laboratories at Purdue University and S-Ram Dynamics collude to produce two state-of-the-art gas cycle refrigeration technologies with indistinguishable performance for various applications. Both technologies explore the use of natural refrigerants eliminating the use hydrofluorocarbons (HFCs) with high global warming and ozone depleting potential, and incorporate oil-free compressors resulting in improved heat exchanger efficiency and eliminate forced oil system requirements.

The first technology is a high performance regenerative air cycle heat pump for cold climates that will be two times more energy efficient than the current the Air-Conditioning, Heating, and Refrigeration Institute's standard, exceeds the Department of Energy cold climate heat pump coefficient of performance, maintains high capacity and performance on a -30°F winter day, and generates customer paybacks in less than four years.

The second technology is a hermetic transcritical carbon dioxide compressor. The novelty of building and testing this type of compressor allows us to fill the gap of knowledge about the fundamental concepts of carbon dioxide compression and obtain detailed performance data to evaluate the performance potential of the transcritical carbon dioxide technology on a system level.

The high performance heat pump is the result of the recent invention of a variable stroke piston compressor and variable expander using S-RAM technology, coupled in a modified Stirling/Ericsson closed cycle invented by ReGen. Purdue will perform heat pump performance modeling using the validated Oak Ridge National Laboratory's (ORNL) heat pump design model, design and commission a test stand and test control software that will be used to conduct tests to assess the heat pump performance and verify proper operation of the control system. Once this is completed Purdue will work with ReGen to optimize the controls for highest system efficiency. Similarly, Purdue will design and commission a hot gas bypass test stand and test control software that will be used to conduct high pressure tests at various motor speeds to evaluate the carbon dioxide compressors performance.

The innovative heat pump will not only eliminate the use of HFCs because air will be the working fluid but has the ability to operate at optimum efficiency under all operating conditions, delivering exceptional part-load and seasonal performance. This heat pump will generate annual energy savings greater than 50% as compared to current heat pump, packaged heating and rooftop units, resulting in a National Total Energy Savings of 1.0 quads for 100% adoption and 0.15 quads for a market penetration of 15%. Like the heat pump, the carbon dioxide compressor and system technology is expected to enable low energy consumption reducing costs with attractive payback periods, continuous high system efficiency and comfort for heating and cooling, permit compact system design. The oil-free aspect of the technologies allow for more diverse system designs, a higher quality air supply, and reduced maintenance costs.

HIGH EFFICIENCY AIR CONDITIONING SYSTEMS FOR HOT CLIMATE REGIONS

Research Assistant: Ammar Bahman

Principal Investigator: Professors Eckhard Groll, James Braun and Travis Horton

ABSTRACT

Air conditioning contributes significantly to building energy consumption in hot climate regions. As the usage of air-conditioning (AC) increases worldwide, it is necessary to find ways to limit its energy consumption for environmental and economic reasons, especially in hot climate regions. However, the system performance decreases with increasing ambient temperature, which makes energy efficient air-conditioning a challenge.

The purpose of this project is to investigate two novel compression technologies for application in high ambient temperature air conditioning. These technologies are liquid flooded compression with regeneration and vapor injected compression with economizing. These two technologies are currently being evaluated at the Ray W. Herrick Laboratories at Purdue for cold climate heat pump applications using R410A as the working fluid. According to preliminary results, the compressor discharge temperature and power consumption are significantly decreased when using these novel compression technologies. The reduced discharge temperature reduces the desuperheating losses in the condenser. In addition, heating capacity and throttling losses are reduced as a result of lower refrigerant qualities entering the evaporator.

Preliminary modeling results indicate that the performance of air conditioning systems with liquid flooding or vapor injected compression in high temperature climate regions can be significantly improved by employing these technologies. Reduced power consumption to meet required cooling loads leads to significant reductions in operational costs. It is expected that either one of the two compression technology will lead to overall COP improvements of approximately 20% at high ambient temperatures,

Other environmentally friendly refrigerants, including both hydrocarbon (R290) and less hazardous refrigerants (R32 and HFO) will be explored as part of this project in combination with the novel compression technologies.

INVESTIGATION OF METHODS TO REDUCE THE EFFECTS OF MALDISTRIBUTION ON EVAPORATOR PERFORMANCE.

Research Assistants: Christian Bach

Principal Investigator: Professors James Braun, Eckhard Groll and Travis Horton

Sponsor: California Energy Commission and U.S. Department of Energy

ABSTRACT

Evaporators are often designed for uniform air and refrigerant flow distribution among the circuits. Some researchers have investigated the optimization of the refrigerant side circuitry to account for airside maldistribution. However, this approach does not address time varying airside maldistributions that occur in rooftop air conditioning units with economizers that mix varying amounts and conditions of outdoor and return air or for low temperature heat pumps or refrigeration equipment that have uneven frost build up on evaporators.

This poster will present results for two different methods that can be used to reduce the effects of airside maldistribution.

One approach, the hybrid refrigerant flow control for individual evaporator circuits, was investigated theoretically and experimentally. For maldistributed conditions, a significant performance improvement was found when compared to an evaporator without hybrid flow control for split-system heat pump, rooftop air conditioning and walk-in cooler applications. However, the experiments also showed that a significant investment needs to be made to optimize the controls and to manufacture the control system.

As a second, less costly approach, interleaved circuitry was investigated theoretically. The basic idea of the interleaved circuitry is to reduce liquid feed-over by interleaving areas that are expected to have increased airside capacity with areas that are expected to have reduced airside capacity on the refrigerant side. The simulations showed that the method can be very effective if the applied maldistribution is identical or close to the profile that was used for the design.

INVERSE MODELING TO SIMULATE FAULT IMPACTS FOR AIR CONDITIONING EQUIPMENT

Research Assistants: Howard Cheung

Principal Investigator: Professor James Braun

Sponsor: National Institute of Standards and Technology

ABSTRACT

Inverse modeling is useful for extending available measurement data to conditions and situations not encountered during testing. In the context of this project, it is used to simulate fault levels, combinations of faults, and operating conditions for vapor compression equipment that were not tested in the laboratory. It provides an accurate and quick simulation of the system response, such as subcooling and power consumption, to different faults, such as low or high refrigerant charge and heat exchanger fouling.

The model is constructed from multiple simplified component models, which are trained from experimental data. Charge tuning is conducted to simulate charge level accurately. The approaches for fault modeling were developed based on previous experimental studies of different faults. The overall system model is solved using optimization algorithms. The modeling approach and predictions have been extensively validated using experimental data from eight different systems.

The modeling tool is useful in evaluating the performance of the fault and detection diagnostics (FDD) tools that are available in the market. The speed of the model enables the generation of a large database of equipment performance over a wide range of environmental and faulted conditions. The database is used by an FDD tool evaluator to assess the performance of diagnostic tools in terms of false alarms, misdiagnoses, etc.

RTU ECONOMIZER DIAGNOSTICS USING BAYESIAN CLASSIFICATION

Research Assistants: Andrew Hjortland

Principal Investigator: Professor Jim Braun

ABSTRACT

Approximately 60% of commercial floor space in the US is served by rooftop air-conditioners (RTUs), many of which utilize outdoor-air economizers to reduce building energy consumption. However, preventative maintenance in the field is uncommon for these types of units and service calls are generally only made for emergencies. It is not uncommon for faults to persist in RTUs without notice, decreasing system efficiency and increasing run-time and operating costs. Poor economizer control, economizer damper failure, and excess outdoor-air contribute to these performance degradations. In order to promote optimal RTU performance and reduce operating costs, an automated fault detection and diagnostics (AFDD) tool has been designed for RTUs with integrated economizers.

- An economizer diagnosis tool using a Bayesian classifier to isolate common economizer faults has been designed. The tool requires four, low-cost temperature sensors installed in the ventilation air-streams as inputs and utilizes damper position control to create system redundancy. By performing functional tests with the damper, the tool is able to diagnose stuck damper faults along with outdoor-, return-, mixed-, and supply-air temperature bias faults. The FDD tool minimizes the probability of making a wrong decision using the Bayesian classifier and also provides a statistical level of confidence in its decision. Using experimental test data, the economizer FDD method performed well at isolating different faults with low frequency of misdiagnoses. It is envisioned that this method could be implemented by the RTU manufacturer in order to meet new economizer FDD requirements, like CA Title 24.

VIRTUAL SENSOR BASED RTU FDD FOR MULTIPLE SIMULTANEOUS FAULT DIAGNOSES

Research Assistants: Woohyun Kim

Principal Investigator: Professor James Braun

ABSTRACT

The primary goal was to develop a complete implementation and demonstration of a fault detection and diagnostic (FDD) system applied to a Rooftop unit (RTU) that incorporates integrated virtual sensors and fault impact evaluation for multiple simultaneous faulty conditions. The specific activities of the project include: 1) develop, implement, and evaluate virtual sensors to be used for fault detection, diagnosis, and fault impact evaluation, 2) demonstrate a complete diagnostic implementation for RTU in the laboratory, 3) develop performance indices that can be used within a decision-support system to assess whether RTU service should be performed.

A virtual sensor uses low-cost measurements and a simple model to estimate a quantity that would be expensive and/or difficult to measure directly. Laboratory tests were performed to evaluate FDD performance and define reasonable thresholds for the FDD system with multiple simultaneous faults to assess whether RTU service should be performed. The tests also quantified the benefits of this technology with measurements of equipment performance (cooling capacity and power, etc.), and demonstrated implementation with low sensor costs.

This work is unique in providing an approach for fault detection and diagnoses of multiple-simultaneous faults along with an assessment of the severity of a fault, which is essential to the service decision making process. Health and economic status reports for equipment can be generated using fault impact indices, such as capacity and energy efficiency performance reduction ratios. In particular, the fault impact indices can be used to assess the economics associated with servicing a unit if faults exist.

METHODOLOGY FOR EVALUATING PERFORMANCE OF DIAGNOSTICS FOR AIR-CONDITIONERS

Research Assistants: David Yuill

Principal Investigator: Professor Jim Braun

ABSTRACT

Diagnostic approaches are being deployed in all areas of technology to indicate potential operating problems, i.e. *faults*. For example, cars have "Check Engine" lights. There is currently a great deal of interest among air conditioner manufacturers, maintenance providers, electric utilities, and energy efficiency regulators to apply diagnostic tools to air conditioners; in particular the residential split systems and light commercial rooftop units that are so widely deployed in the US. As fault detection and diagnosis (FDD) tools become more widespread in the marketplace and become required by codes and standards, a key question needs to be addressed: how well do these tools work?

A project led by Professor Braun is addressing this question in six steps:

1) Develop a methodology for evaluation. The methodology includes enumeration of the rates of *False Alarm*, *Misdiagnosis*, *Missed Detection*, and *Detection without Diagnosis* with a focus on the significance of the fault on equipment performance. The rates come from multiple test cases fed to an FDD tool. These test cases cover a range of different operating conditions, fault types and intensities, and different air conditioners. The evaluation focuses on the FDD protocol (excludes hardware).
2) Gather a database of reliable inputs to feed to candidate FDD tools
3) Generate models that accurately simulate performance of air conditioners operating with typical faults present. These models allow variation of operating conditions, fault types, and fault intensities for each individual air conditioner, so that the input space can be controlled.
4) Test the methodology by performing case studies on existing FDD approaches
5) Develop meaningful performance metrics to succinctly communicate overall performance to potential FDD adopters or specifiers
6) Create software that implements the evaluation methodology, interfacing with the input library and the candidate FDD protocols.

Case study results show significant room for improvement in some widely used FDD approaches. The project's output is expected to provide many benefits:

- Aid FDD developers by providing a yardstick by which to measure their FDD performance
- Allow regulators to specify FDD performance levels, and to set meaningful performance targets
- Increase adoption of FDD
- Reduce the number of air conditioners operating with faults, thus saving energy, reducing operating costs, and preventing atmospheric damage

MECHANISTIC MODELING OF A DUAL-UNIT VARIABLE-SPEED DUCTLESS HEAT PUMP SYSTEM

Research Assistants: Howard Cheung

Principal Investigator: Professor James Braun

Sponsor: Electric Power Research Institute

ABSTRACT

A modeling approach for dual-unit variable-speed ductless heat pump (DHP) systems has been developed. DHPs use variable-refrigerant-flow technology and can control individual loads within different zones of a residence. As such, they are an efficient alternative to current central air systems for residential buildings. However, complete performance maps for these units are not readily available and it is difficult to develop models from measurements because of the complexity and black-box nature of the capacity controls for multiple indoor units and the outdoor unit. This project has developed a semi-empirical modeling approach for predicting the performance of DHPs that relies on a combination of physical parameters and measurements.

The method is developed by decoupling the system into mechanistic component models and tuning the component model parameters with experimental data. The compressor speed and expansion valve openings of the system under different conditions are determined using optimization algorithms. The simulation results are compared with the experimental data to examine the accuracy of the simulation.

The modeling approach is useful in understanding how dual-unit DHPs respond to different operating conditions in terms of valve and compressor speed controls and overall performance. The tool is a useful approach for the minimizing the time-consuming and costly experimental testing of dual-unit DHP systems needed to fully characterize performance.

LOW-COST VIRTUAL POWER AND CAPACITY METER FOR ROOFTOP UNITS

Research Assistants: Howard Cheung

Principal Investigator: Professor James Braun

Sponsor: Department of Energy – Energy Efficient Buildings Hub

ABSTRACT

A low-cost virtual sensor for power consumption and cooling capacity of rooftop units (RTUs) in small commercial buildings is under development. The sensor package would be designed so that its high-cost components can be reused in the future to save cost, while the rest of the package, mainly assembled with low-cost temperature sensors, provides accurate and reliable outputs of power consumption and cooling capacity using models.

To extend the applicability of the sensor to a wide range of conditions and minimize training requirements, semi-empirical compressor models are trained using power and temperature readings. A self-learning algorithm has been constructed that automatically determines when sufficient data has been collected for accurate training of the models. After the training period, the direct power measurement is removed and the virtual sensor outputs power consumption and capacity using only the low-cost temperature readings.

The virtual sensing approach reduces the cost of acquiring these important measurements in the field, which are needed for advanced monitoring, diagnostics, and optimal control.

SEMI-EMPIRICAL INVERSE MODEL FOR DX UNIT PERFORMANCE IN RESIDENTIAL BUILDINGS

Research Assistants: Zhidan Zhao

Principal Investigator: Professor W. Travis Horton

ABSTRACT

Residential buildings are large consumers of electric energy. About 40% of the electricity generated in the U.S. is consumed by residential buildings every year (U.S. EIA, 2010); and about 21% of that electricity is consumed by air conditioning equipment (U.S. EIA, 2005). Direct Expansion split air conditioning systems occupy the largest portion of the cooling market for residential buildings, so modeling this kind of equipment is necessary and useful to identify and improve the system performance and operating characteristics. In this area of research, inverse models are generally used. Inverse models are normally derived from empirical behavior and expressed in terms of one or more driving forces and a set of empirical parameters that are "identified" using measurements. Once identified, a model can be used for a variety purposes, including performance monitoring, diagnostics, retrofit analysis, measurement and verification of efficiency improvements, and on-line control optimization. In this study, a semi-empirical inverse model or a "grey-box" model is developed to estimate the power consumption of a direct expansion (DX) air conditioning system that handles the cooling requirement of a residential building. This "grey-box" model approach requires fewer parameters and training data and provides better extrapolation than other popular empirical or "black-box" models. The model is based on physical system performance parameters and not only on a single compressor or coil, so it can provide a clear performance map of the air conditioning system in residential buildings. The training and validation data used for model construction in this paper comes from manufacturer's detailed DX unit performance models, which closely matches equipment performance in the field.

AN INTEGRATED SYSTEM OF VAPOR-COMPRESSION CHILLER AND ABSORPTION HEAT PUMP FOR EFFICIENCY IMPROVEMENT

Research Assistants: Yi-Shu Kung

Principal Investigator: Professor Dr. Ming Qu

ABSTRACT

Subcooling the refrigerant from the condenser in a vapor compression refrigeration system could be an effective approach to improve the coefficient of performance (COP). The effort in this research has investigated the COP improvement of a Vapor-compression chiller and Absorption heat pump Integrated System (VAIS) by using the approach. The VAIS uses the chilled water from the absorption heat pump (AHP) to subcool the refrigerant of the vapor-compression chiller (VC) by adding a heat exchanger, called a subcooler, between the condenser and the expansion valve of the VC. Additionally, the VAIS can also provide useful hot water provided from the AHP.

A test bed of the VAIS is under construction at Purdue University to test system performance. A series of tests will be conducted and the experimental data will be collected from the tests. Meanwhile, models for the VAIS based on thermodynamic and heat transfer principles were developed to analyze the experimental data and further for the prediction of the system performances at variant conditions. These models developed are able to predict the working conditions of the VAIS including temperature, pressure, flow rate, enthalpy, energy, and others. The validated models will be also used for the establishment of VAIS control system and life cycle assessments.

The modeling results indicate the VAIS of the test bed can improve the COP of the VC by 13-28% depending upon different operation conditions. Additionally, the hot water produced by the VAIS shows additional strength of the technology. The hot water can be used for domestic hot water, swimming pool or space heating with additional heat inputs. Since the VAIS can provide both heating and cooling simultaneously, it is especially suitable for buildings with both demands at the same time like hotels, chain restaurants, and supermarkets.

THE DEVELOPMENT OF ABSIM (ABSORPTION SIMULATION SOFTWARE)

Research Assistants: Zhiyao Yang

Principal Investigator: Professor Ming Qu

ABSTRACT

ABSIM (an acronym for ABsorption SIMulation), a computer code created in 1989 and designed for the simulation of absorption systems at steady state in both flexible and modular form, is updated with a user-friendly graphical interface and compatibility to multiple computer platforms, along with more functions such as parametric table and plot developed within.

The new ABSIM is built around the original version's core calculation code. By using XML database extensively, the software provides excellent modular features that allow user-defined physical component model be easily generated and plugged into the system. Along with an interactive and user-friendly graphical interface developed with Qt graphics library, the software enables user to set up various system cycles with the 29 built-in components and any customized components, carry out simulation as well as parametric study, and then plot the results onto property charts of working fluid.

The software's compatibility to new component models provides excellent robust feature for future expansion of the absorption cooling technology, which proves an energy-saving alternative in air-conditioning applications. This software will significantly improve the efficiency of researchers and engineers to simulate and design systems, thus expedite the development and application of the technology.

MULTI-OBJECTIVE OPTIMAL DESIGN OF A SOLAR ABSORPTION COOLING AND HEATING SYSTEM UNDER UNCERTAINTIES

Research Assistants: Donghao Xu, Yin Hang, Fu Zhao

Principal Investigator: Professor Ming Qu

ABSTRACT

Solar absorption cooling and heating (SACH) systems provide building heating and cooling by using solar energy. It has great potential to reduce energy consumption and environmental impacts from buildings. However, currently they still stay at development and demonstration stage due to the nature of the complex systems and limited practical experiences. The main obstacle to broadly applying the technology is the lack of design guidelines or the evaluation platform for people to design the system. To find the optimal design, optimization is a necessary approach. However, some parameters in objective functions, such as energy source prices in the future, are incompletely known. Many optimizations are subject to uncertainties of these parameters and thus the results may not hold. Therefore, to achieve a robust result, uncertainty information should be incorporated into the optimization. Robust optimization is a field of optimization that seeks robustness against uncertainties. The work in the paper utilized the robust optimal design techniques to design a SACH system under uncertainties in order to maximize the system overall performance at aspects of energy, economic, and environment. The uncertain parameters considered include life span of SACH systems, energy consumption and CO_2 emission during operation stage, as well as fluctuation of energy market and financial conditions. The optimal solutions are identified and presented. The study indicates that the uncertainties considered do not have significant impact on the SACH design. Therefore, deterministic optimization can be sufficient for the SACH design if the uncertainties remain at the same level.

MODELING AND EXPERIMENTAL ANALYSIS OF PASSIVE CHILLED BEAMS

Research Assistants: Janghyun Kim

Principal Investigator: Professors James Braun, Travis Horton and Athanasios Tzempelikos

ABSTRACT

Radiant heating and cooling systems are one approach for reducing building energy consumption. While radiant heating has been successful worldwide, radiant cooling is only popular in northern Europe and just being introduced in other continents and countries. One of the promising technologies of radiant ceiling cooling system is a chilled beam system. The chilled beam can be categorized into two types; passive type and active type. While active chilled beams include forced air movement such as fan operation to enhance heat transfer mechanism, passive chilled beams rely on radiation and natural convection only for sensible heat transfer and do not employ active fans. In this study, passive type chilled beams are only considered. The optimum sizing and location of the chilled beams needs to be carefully determined according to the space geometry, occupied areas and window positions since it will affect both the cooling performance and thermal comfort of the space. Due to the fact that passive chilled beams are particularly difficult to model accurately because primary heat transfer mechanisms of radiation and natural convection are strongly coupled to the specific characteristics and conditions within the spaces where they are installed, extensive study including both experiment and simulation of chilled beam application is required. Thus, in this study, standard performance of a passive chilled beam will be measured from a steady-state conditioned experiment. Then the measured data will be used for a development of passive chilled beam model that can be implemented with whole building simulation programs, such as TRNSYS.

ENERGY MODELING OF PHOTOVOLTAIC THERMAL SYSTEMS WITH CORRUGATED UNGLAZED TRANSPIRED SOLAR COLLECTORS

Research Assistants: Siwei Li, Sam Currie

Principal Investigator: Professor Panagiota Karava

ABSTRACT

Building-integrated photovoltaic-thermal (BIPV/T) systems with unglazed transpired solar collectors (UTCs) can be a key solution to the energy and environmental challenges associated with buildings. So far, although the energy saving potential of such systems is significant, no systematic thermal analysis model has been developed to accurately predict their performance and, consequently, to enable optimal system design, integration with building operation simulation and smart control. In this research, detailed physical energy models are developed based on the thermal network representation with the energy balance equations solved using a fully explicit finite difference scheme. Nusselt number and effectiveness correlations, which are essential components of the models, have been obtained from experimentally validated three-dimensional, Reynolds-Averaged Navier–Stokes (RANS), Computation Fluid Dynamics (CFD) simulations, using high resolution grids and the Renormalization Group Methods k-ε (RNG k-ε) turbulence closure model, to represent both the exterior and interior convective heat transfer processes. The energy models are then validated with experimental data obtained from a BIPV/T installation at the Architectural Engineering Labs at Purdue. The models are implemented in TRNSYS as a user-defined component to enable simulations for performance analysis and integration with dynamic control algorithms. The Living Labs are considered as a case study and model-based predictive control strategies are developed for a BIPV/T system integrated with the building operation, a thermal energy storage tank and an air-to-water heat pump.

PERFORMANCE OF HEAT EXCHANGERS AND HEAT SINKS AFTER AIR-SIDE FOULING AND CLEANING

Research Assistants: Harshad Inamdar

Principal Investigator: Professors Eckhard A. Groll and Suresh V. Garimella

Sponsor: Cooling Technologies Research Center

ABSTRACT

Fouling of enhanced surface heat exchangers (HX) and heat sinks (HS) by particulate matter may significantly reduce their performance. Hence, the effect of particulate fouling and subsequent cleaning on the performance of finned heat exchangers and heat sinks is being investigated. It is anticipated that factors such as type of HX/HS, air velocity, air humidity and concentration of dust in air will impact the fouling and subsequent performance degradation of heat exchangers and heat sinks.

The heat exchangers being tested are installed in the wind tunnel, where the air-side parameters, such as velocity, temperature and humidity, can be controlled. ASHRAE standard test dust is then injected into the air stream at a pre-determined rate which leads to fouling of the heat exchanger. The mass of dust deposition on, pressure drop across, and heat transfer through the heat exchangers is measured and compared to evaluate degradation in performance, and correlate the degradation to the extent of fouling on the HX/HS. In addition, a heat exchanger simulation model will be developed based on first principles to predict the deposition rate, the increase in pressure drop and the decrease in performance of the HX/HS as a function of time.

With this project, and with results obtained from similar projects done in the past by the PI, it is envisioned to predict the extent of fouling of HX/HS being operated in the field, and set target cleaning schedules based on the maximum degradation in performance of the HX/HS that can be tolerated by the system in which the HX/HS is installed. A comparison of prior-fouling and post-cleaning performances will also enable an understanding of the efficacy of cleaning procedures, which could modify how the field life of an HX/HS is measured.

LIQUID FLOODED ERICSSON POWER CYCLE

Research Assistants: Nelson James

Principal Investigator: Professors James Braun, Eckhard Groll and Travis Horton

ABSTRACT

This research examines the use of liquid flooding to create a high efficiency Ericsson power cycle. The introduction of significant amounts of liquid into the compression and expansion processes of a gas leads to quasi-isothermal behavior approximating that of an Ericsson cycle. Through developing thermodynamic models integrating this phenomenon into an overall cycle, optimal system conditions were identified to maximize the thermal efficiency for various working fluid pairs. It was found that the performance of the power cycle depends greatly on the component efficiencies of the liquid-flooded expander and compressor. There has been little work in regards to liquid-flooded expansion at the elevated temperatures of interest to the Ericsson cycle. To prove the feasibility and gain a better understanding of high temperature liquid-flooded expansion, a test stand is being developed to investigate the performance of a scroll expander operating at 350^{o}C with nitrogen and thermal oil. A semi-empirical model of the scroll expander will be created using the experimental results to extrapolate the scroll expander's performance to other operating conditions. This research will lead to a better understanding of the potential benefits of liquid flooding in a power cycle and may lead to the implementation of Ericsson cycles as low cost, efficient power cycles for distributed power generation. Of particular interest is solar thermal power generation, where the heat transfer fluid can be directly feed into the Liquid Flooded Ericsson cycle, reducing the need for an additional heat exchanger and driving down cost.

ANALYSIS OF A ROTATING SPOOL EXPANDER FOR ORGANIC RANKINE CYCLES IN HEAT RECOVERY APPLICATIONS

Research Assistants: Abhinav Krishna

Principal Investigator: Professor Eckhard Groll

Sponsor: Torad Engineering, LLC

ABSTRACT

The increasing cost of energy, coupled with the recent drive for energy security and climate change mitigation have provided the impetus for harnessing renewable energy sources as viable alternatives to conventional fossil fuels. Furthermore, recovering heat that is discharged from power plants, automobiles and various other industrial processes is of growing interest. Nevertheless, technologies attempting to provide small scale heat recovery solutions have seen very limited commercialization. This is broadly due to two reasons: lack of historical research and development in the area of waste heat recovery and small scale power generation due to technical and cost impediments; and technical challenges associated with scaling the technology from utility scale to commercial scale, particularly with regard to expansion machines (turbines). However, due to rising primary energy costs and the environmental premium being placed on fossil fuels, the conversion from low-grade heat to electrical energy as well as small scale distributed power generation is of increasing interest. In this regard, this project focuses on a novel rotating spool expansion machine at the heart of an Organic Rankine Cycle, which in turn is used as a heat recovery system.

A comprehensive simulation model of the rotating spool expander is being developed. The spool expander provides a new rotating expansion mechanism with easily manufactured components. Apart from efficiency improvements compared with other rotary machines, the spool expander also has the ability to control the expansion ratio using a novel mechanically-driven suction valve mechanism. A further advantage is the relocation of the face sealing surfaces to the outer radius of the device. A detailed analytical geometry model of the spool expander and the suction valve mechanism is analyzed. This geometry model forms a part of a comprehensive model that includes submodels for friction, leakage, and heat transfer. The results of the comprehensive model will be validated using experimental data from a prototype expander. Given these promise of the technology, this project explores the design space using both a simulation based approach as well as an experimental prototype for concept validation.

Design and Construction of an Organic Rankine Cycle Test Stand for Scroll Expander Performance Testing

Research Assistants: Anchalika Pathak

Principal Investigator: Professor Eckhard Groll

Sponsor: Cummins Inc.

ABSTRACT

Organic Rankine Cycles (ORC) are one of the promising technologies to convert waste heat (typically a low grade heat with a temperature range between 100-220^{o}C) into useful work.

The typical layout of an ORC includes a pump to elevate the pressure of the refrigerant, an evaporator which exchanges heat against the waste heat, an expander which expands the superheated refrigerant from high to low pressure to generate shaft power output and a condenser to condense the refrigerant.

An experimental test setup is designed and constructed as part of this project to investigate the performance of an ORC using a scroll expander. Scroll expanders are fixed volume ratio expanders that have consistently shown high efficiencies in literature. They are known for operating more smoothly, quietly, and reliably than conventional devices and have better volumetric efficiencies. The scroll expander to be supplied by Air Squared is an oil-free expander with few moving parts and low noise and vibration.

The test stand is designed in such a way that it can be used in the future to conduct performance testing of different expanders. Thus, it will facilitate the future research of ORCs at the Ray W. Herrick Laboratories.

METHODS OF INCREASING NET WORK OUTPUT OF ORGANIC RANKINE CYCLES FOR LOW-GRADE WASTE-HEAT RECOVERY

Research Assistants: Brandon Woodland

Principal Investigator: Professors James E. Braun, Eckhard A. Groll and W. Travis Horton

Sponsor: Herrick Foundation

ABSTRACT

To meet the growing demand for energy, it is important to consider a diversity of sources. However, many energy sources are of a lower grade or quality than traditional fossil fuels. This means they cannot be employed directly in conventional power plants. One example of a low-grade heat source is process waste heat. This often comes at temperatures in the range of 80 °C – 300 °C. An organic Rankine cycle (ORC) is well-suited to converting this low-grade energy into useful work. It operates on the same principle as a steam power plant. However, instead of steam, an ORC uses an organic working fluid such as a refrigerant or a hydrocarbon.

Without a means of thermal storage, process waste heat must be used as it becomes available. Any unused heat will be discarded. In this situation, thermal efficiency, the most common measure of heat engine performance, is no longer relevant. Instead it is more important to maximize the net power produced by the ORC. This design objective reveals a different path toward system improvement than the conventional approach of maximizing thermal efficiency.

A generalized model was developed that accounts for the maximum heat recovery rate as a function of particular working fluid and operating conditions. From this analysis, two alternative ORC configurations were identified which yield higher net power than a typical ORC for a given waste heat temperature and flow rate: the ORC with two-phase flash expansion and the ORC with working fluid mixtures (ZRC). Both configurations take advantage of the temperature profiles of the working fluid, the waste heat fluid, and the ambient air to achieve higher heat recovery rates and higher net power output.

Experimental testing will first be conducted on the ZRC to validate the predictions of the above model for 80 °C – 100 °C source temperatures. The ZRC will then be modeled in detail. The detailed model provides insight into off-design operation and sensitivity of the system to design parameters.

This work could improve the economics of waste heat recovery. More power from a given waste heat source could encourage more investment in the technology and better energy utilization. The design methodology has broader applications. For example, it can be applied to high-temperature waste heat recovery from internal combustion engines. The same methodology, along with the proposed cycle modifications, could also potentially be applied to distributed cogeneration systems using solar or another renewable heat source.

PREDICTING TRANSIENT PARTICLE TRANSPORT IN ENCLOSED ENVIRONMENTS WITH THE COMBINED CFD AND MARKOV CHAIN METHOD

Research Assistants: Chun Chen

Principal Investigator: Professor Yan Chen

ABSTRACT

To quickly obtain information about airborne infectious disease transmission in enclosed environments is critical in reducing the infection risk to the occupants. This study developed a combined Computational Fluid Dynamics (CFD) and Markov chain method for quickly predicting transient particle transport in enclosed environments. The method first calculated a transition probability matrix using CFD simulations. Next, the Markov chain technique was applied to calculate the transient particle concentration distributions. This investigation used three cases, particle transport in an isothermal clean room, an office with an Under-Floor Air-Distribution (UFAD) system, and the first-class cabin of an MD-82 airliner, to validate the combined CFD and Markov chain method. The general trends of the particle concentrations versus time predicted by the Markov chain method agreed with the CFD simulations for these cases. The proposed Markov chain method can provide faster-than-real-time information about particle transport in enclosed environments. Furthermore, for a fixed airflow field, when the source location is changed, the Markov chain method can be used to avoid recalculation of the particle transport equation and thus reduce computing costs.

INVERSE PREDICTION AND OPTIMIZATION OF THERMAL ENVIRONMENT IN AN AIRLINER CABIN BY USING THE CFD-BASED ADJOINT METHOD

Research Assistants: Wei Liu

Principal Investigator: Professor Yan Chen

ABSTRACT

By using the measured flow and temperature field in the first-class cabin of a functional MD-82 commercial airliner in our recent study, the computed PMV value at the occupant region is between 0.8 ~ 1.0 that means slightly warm. Therefore, to improve the thermal comfort in the aircraft cabin, this investigation tried to redesign the ventilation system and applied the adjoint method to find the optimal inlet air conditions. By setting the occupant region as the target domain and the inlet air velocity and temperature as design variables, this study conducted the optimization with/without limitations of the air flow rate and inlet air temperature. For each condition, this study conducted the optimization with different initial inlet air conditions to find the global solution. In each design cycle, this study computed the Navier-stokes equations for 5000 iterations and the adjoint equations for 1000 iterations, which is a trade-off between the convergence of the calculations and computing effort. The computed results show that with different initial conditions, the calculations lead to similar optimal inlet air conditions for each condition. Comparing the optimal inlet air conditions of the two conditions, the optimal angles between the inlet air velocity vector and the vertical line are between 55º ~ 59º and the optimal inlet air temperature is 290±0.6 K. For the optimization without limitation, an increased air flow rate by 30% would improve the overall thermal comfort greatly.

IMPROVEMENT OF FAST FLUID DYNAMICS WITH A CONSERVATIVE SEMI-LAGRANGIAN SCHEME

Research Assistants: Mingang Jin

Principal Investigator: Professor Yan Chen

ABSTRACT

Fast Fluid Dynamics (FFD) is an excellent tool for performing fast airflow simulations required by the building industry. Although FFD can provide indoor airflow simulations with reasonable accuracy, it has been found that FFD may fail to preserve conservation for energy and species transport because of the non-conservative semi-Lagrangian scheme. This study thus proposed a conservative semi-Lagrangian scheme that applied a new mass-fixing method beyond standard semi-Lagrangian scheme to restore conservative advection. The conservative semi-Lagrangian scheme was then implemented in FFD to achieve conservation in airflow simulations. Our numerical tests show that the proposed scheme was indeed conservative with negligible impact on the accuracy of the flow prediction. The results also show that FFD with the conservative semi-Lagrangian scheme can effectively enforce the energy and species conservation for indoor airflow simulations.

CFD INVESTIGATION ON TURBULENT STRATIFIED JETS

Research Assistants: Zhu Shi

Principal Investigator: Professors Qingyan (Yan) Chen and Jun Chen

ABSTRACT

Stratified flows exist prevalently in areas including environmental, geophysical and chemical engineering fields. Studying the stratified flows is very important to understand the process of the mixing and to improve design of indoor environment, geophysical construction, and chemical product. This investigation tests the performance of 7 turbulence models in both weak and strong stratification flows, by making comparisons between simulation results with experimental data. The predicted velocity, turbulent kinetic energy and Reynolds stresses distributions are compared with benchmark experiments to evaluate the performances of the models. In weak stratification case, all the 7 models can give good prediction of velocity distribution. But in strong stratification case, the velocity distribution is over-predicted in unstable stratification region by RSM and LES. As to second order flow characteristics, overall, SST $k-\omega$ model, RNG $k-\varepsilon$ model and RSM model give the best predictions, although the predictions in unstable stratification regions are worse than in stable stratification regions. This study also introduces a new turbulent Schmidt number model for stratified jets, and its performance on predicting density distribution is evaluated and compared with using constant turbulent Schmidt numbers. Besides, the computational cost of the models and the additional cost of adopting the turbulent Schmidt number model are discussed. In addition, the vorticity and entrainment predictions in both weak and strong stratification jets are analyzed through comparisons with experimental data and empirical formula.

A SEMI-EMPIRICAL MODEL FOR STUDYING THE IMPACT OF THERMAL MASS AND COST-RETURN ANALYSIS ON MIXED-MODE VENTILATION IN OFFICE BUILDINGS

Research Assistants: Haojie Wang

Principal Investigator: Professor Jun Chen

ABSTRACT

Mixed-mode ventilation that combines natural ventilation and mechanical ventilation has great potential to save cooling energy when compared to mechanical systems and is more reliable than natural ventilation systems. This paper presents a semi-empirical model for studying the impact of window opening area, insulation, and thermal mass on the cooling energy saving of mixed-mode ventilation for three office buildings in different types of U.S. climates using EnergyPlus simulations. The results show that electricity use can be reduced by 6-91% depending on the climate. In addition to climate, thermal mass has a large impact on the performance of mixed-mode ventilation. This investigation developed a semi-empirical model to predict the impact of thermal mass on energy use, and optimized the thermal mass for maximum monetary return based on the model.

MODEL PREDICTIVE CONTROL STRATEGIES FOR BUILDINGS WITH MIXED-MODE COOLING

Research Assistants: Jianjun Hu

Principal Investigator: Professor Panagiota Karava

Sponsor: DOE (GPIC Hub for Energy Efficient Buildings), Purdue Research Foundation

ABSTRACT

Mixed-mode (MM) cooling refers to a hybrid approach for space conditioning, employing a combination of natural ventilation, driven by wind or thermal buoyancy forces, and mechanical systems. Effective implementation of this technology requires intelligent controls to minimize energy use and maintain occupant thermal comfort. Existing techniques for mixed-mode buildings are heuristic, i.e. based on fixed schedules that are not optimized for a particular building or climate and may lead to increased operating costs or occupant discomfort. This issue can be overcome with the use of more advanced control strategy such as model predictive control (MPC). MPC is particularly suitable for slow response dynamic systems, such as MM buildings with high levels of exposed thermal mass. The present study investigates the performance bounds of MPC strategies in buildings with mixed-mode cooling through an offline deterministic framework and to also demonstrate real-time MPC application in a lab building. A detailed dynamic model based on finite difference method and the linear time-variant state-space formulation is developed for a multi-zone building with mixed-mode cooling. One efficient optimization method progressive refinement is used to facilitate the MPC implementation in buildings with mixed-mode cooling. The offline simulation results show that MPC can significantly reduce the cooling requirements compared to baseline night setback control while maintaining the operative temperature during the occupied period within acceptable limits. On the contrary, rule-based control strategies for the window opening position, based on simple heuristics for the outdoor conditions, create an increased risk of overcooling with lower thermal comfort acceptability. The methodologies developed in the study would eventually become a benchmark case study for the MPC application in real building.

OZONE-INITIATED CHEMISTRY IN ENCLOSED ENVIRONMENT

Research Assistant: Aakash C. Rai

Principal Investigator: Professor Qingyan (Yan) Chen

Sponsor: Federal Aviation Administration (FAA)

ABSTRACT

Ozone is a major air pollutant that poses significant health concerns for humans. Ozone exposure has been found to be associated with respiratory problems such as asthma, bronchoconstriction, airway hyperresponsiveness, and inflammation. The issue of ozone exposure is further exacerbated by the fact that its reaction byproducts in the indoor environment can be even more harmful than ozone itself. Humans themselves constitute an important site for ozone-initiated chemistry through the surface reaction of ozone with human skin, hair, and clothing. Hence, this research was undertaken to characterize ozone reactions with soiled (human-worn) clothing under simulated environmental conditions. We conducted experiments to quantify ozone consumption and generation rates of its associated byproducts from reactions with a soiled T-shirt. It was found that these ozone reactions generated Volatile Organic Compounds (VOCs) and sub-micron particles, which were significantly affected by the environmental conditions. The results are useful for accessing the exposure to occupants from ozone reaction chemistry in different enclosed environments (such as buildings, aircrafts, etc.) and developing risk mitigation techniques.

SOLAR-ASSISTED AND THERMALLY-INTEGRATED APPLIANCE SYSTEM WITH CENTRALIZED THERMAL STORAGE

Research Assistants: Stephen Caskey and Giulia Marinello

Principal Investigator: Professors Eckhard A. Groll and William J. Hutzel

Sponsor: California Energy Commission and U.S. Department of Energy

ABSTRACT

The aim of this project is the analysis, conceptual design, and experimental validation of a thermally integrated residential appliance (TIRA) system using centralized thermal energy storage coupled with solar PVT utilization. The residential sector of the United States includes over 114 million homes accounting for over 22 quads of primary energy use in 2010 (2011 DOE/Energy Efficiency and Renewable Energy *Buildings Energy Data Book* [BED]), Table 2.1.5). Primary energy use for heating water, household refrigerator/freezers (RFs), and wet cleaning (dishwashers, clothes dryers and clothes washers) used about 24% of this total. Application of the TIRA concept would enable significant reduction in residential energy consumption.

Typically, RFs reject heat to indoor air, resulting in relatively high condensing temperatures and energy use. Modifying an RF to reject heat to the home's water main supply via a TIRA system would enable an estimated 5 to 10% improvement in efficiency, reducing R/F energy consumption by up to 10%. Moreover, the heat rejected to the water could be recovered and used to help offset the energy required to supply hot water needs. Clothes dryers typically operate using either inefficient electric resistance heat or heat from combustion of natural gas, rejecting moist and heated air to the surrounding environment. By implementing a heat pump utilizing the TIRA system as a heat source to provide heat for electric dryers, it is conservatively estimated that their energy consumption could be reduced by 25–30%. Additionally, the waste heat in the vent stream (estimated at 20–25% of total input energy) could be captured by the TIRA system and used to preheat water or for other purposes. Residential hot water is typically provided by either storage electric or gas water heaters (WHs) or by on-demand gas tankless WHs. Alternate renewable and efficient means to heat water have been developed, namely solar systems and electric heat pump WHs (HPWH). The TIRA concept would include these advanced approaches and help facilitate their wider market dissemination. The DOE/BTO research and development roadmap for solar WH established a goal of achieving 40% primary energy savings in cold climates vs. conventional gas WHs; savings in warmer zones (and overall national average savings) should be higher, approaching 50%. Using the TIRA system to provide recovered thermal energy as the source for an electric heat pump WH, it is conservatively estimated that its efficiency could be increased by 5 to 10%.

Assuming the TIRA system could be applied to all single-family homes (~72% of total residences), the technical potential primary energy savings are estimated at ≥0.79 quad/year or almost 4% of the 2010 residential sector total (0.50 quad of natural gas and 0.29 quad of electricity).

VISUAL COMFORT ASSESSMENT IN SPACES WITH SMART FAÇADE CONTROLS

Research Assistants: Iason Konstantzos, Ying-Chieh Chan

Principal Investigator: Professor Thanos Tzempelikos

ABSTRACT

Visual comfort is one of the main priorities when designing working and living environments. Glare from daylight in perimeter building zones highly affects productivity and occupants' comfort. One of the commonly used and convenient ways of solar protection and glare control is employing shading devices. The goal of this research is to assess and predict visual discomfort in perimeter zones with different façade configurations and automated shading controls, and develop improved design guidelines.

Recently, a new glare index named Daylight Glare Probability (DGP) has been partially supported by experimental studies and considers both illuminance at the eye level and intensity and relative position of luminous sources. We have developed models for calculating DGP with different building configurations and advanced façade controls. The models are able to run for the entire year and provide annual glare evaluations. The results are validated by full-scale experiments, including the use of a High Definition Camera (equipped with a fisheye lens to capture the field of view) for luminance mapping and daylight glare evaluation under different shading scenarios. These images are then processed with specialized software to calculate DGP. Given the fact that DGP strongly depends on the position of the observer and the direction of the line of sight, the modular simulation method allows for various positions of the observer to be investigated so that glare-sensitive locations (or control algorithms) can be identified.

We will conduct a series of physical (indoor environmental variables) and human subject experiments (web surveys and interviews) in the new Living Labs and other spaces to evaluate visual comfort, improve existing indices and develop design recommendations for office spaces with daylight provision.

ANNUAL HVAC EQUIPMENT PERFORMANCE COMPARISON FOR EXISTING COMMERCIAL BUILDINGS

Research Assistants: Bonggil Jeon

Principal Investigator: Professor W. Travis Horton

Sponsor: DOE – Energy Efficient Buildings Hub

ABSTRACT

According to the U.S. Energy Information Administration over 70% of existing commercial buildings across the United States are more than twenty years old, with many of these buildings soon in need of renovation. These old buildings consume about 20% of the United States primary energy, which means there is a great potential for energy savings with integrated technologies and building retrofit solutions, such as HVAC and envelope integration, and window and lighting integration. The primary focus of this study is to compare the annual performance of different types of HVAC equipment in existing commercial buildings, and to identify appropriate HVAC systems that could be effectively retrofit into different commercial building types. Annual energy simulation results from the TRNSYS® software package are being utilized to analyze the different HVAC retrofit options. In one case study, an HVAC system option referred to as the “Poor Man’s VAV” will be evaluated for retrofit in the Philadelphia Business Technology Center (PBTC). One major concern for this system is how to control the supply fan static pressure as terminal dampers open and close in response to thermostat and occupancy sensors. Comparison of the annual energy consumption between the original HAVC system and the proposed “Poor Man’s VAV” system in PBTC will inform the selection of retrofit options based on higher performance and cost effectiveness.

OPTIMIZATION METHODOLOGY FOR ENERGY-EFFICIENT HOUSING

Research Assistants: Yeon Jin Bae

Principal Investigator: Professor W. Travis Horton

ABSTRACT

As energy consumption in the building sector across the United States continues to increase, energy modeling and simulation software is being incorporated more regularly into the building design process to simulate thermal loads and predict annual energy consumption. The greatest benefit of using numerical models lies in their potential ability to provide design engineers with feedback regarding how best to optimize these very complex systems. Energy simulation programs typically require hundreds of design parameters as input, which means they are not normally utilized at a very early design stage because many of the parameters are still uncertain. Since any given building project can include a large number of design parameters, and each parameter may have a large number of possible values, it is impossible, because of computational time limitations, to do exhaustive search in this design space to find the parameters that optimize the building design subject to various project objectives and constraints. Optimization methods must be employed to find the best combination of design variables to achieve the desired objectives. Past researchers have identified several applicable building energy optimization methods but the long computational processing time remains as a major challenge to the more widespread use of this technique by both researchers and practitioners. The objectives of this study are to perform an optimization of energy efficient residential construction, to utilize a particle swarm optimization algorithm and to use complex building energy simulation models in conjunction with real world cost data(material cost) across as many climates as possible to reach as reliable, and wide a solution space as can be achieved. The challenge and focus of the future work is to improve the performance of the optimization method, possibly through variable screening and algorithm hybridization, so that the user can have greater freedom in selecting variables and optimization goals, extracting more useful information from the simulation results, and acquire the desired results in a time effective manner. Cost modeling will be improved with regards to adding of replacement and maintenance costs as well as labor cost.

DEVELOPMENT AND ASSESSMENT OF HEURISTIC CONTROL STRATEGIES FOR A MULTI-ZONE COMMERCIAL BUILDING EMPLOYING A DIRECT EXPANSION SYSTEM

Research Assistants: Jie Cai

Principal Investigator: Professor Jim Braun

ABSTRACT

Direct expansion (DX) cooling units are widely used in small and medium size commercial buildings. In this study, offline optimization was employed to develop heuristic control strategies for a multi-stage DX unit coupled to a variable-air-volume (VAV) air-handling unit (AHU) that serves multiple zones within a medium size commercial building. A gray-box model was first developed for the DX system using on-site data that integrates component models into a system model. This modeling approach was chosen over more empirical methods to enable training with limited available data and to ensure good extrapolating performance. This is a general modeling approach that can be applied to other DX units. The gray-box model was used for optimization of the DX unit and an optimal map was generated. Based on the optimal map results, a simple heuristic strategy was identified for this system that involves resetting the supply upwards with constraints of meeting the zone. The optimal results indicate higher efficiency can be achieved at higher supply air temperature. Based on this fact, a heuristic controller was implemented which would operate the system at the highest possible supply air temperature while meeting the load and dehumidification requirements. To assess the energy saving of these optimal and heuristic controller compared to the current control law which enforces a constant supply air temperature setpoint, we setup a simulation platform which coupled the HVAC and envelope models and tested these different controllers. More than 10% energy saving was obtained by just resetting the supply air temperature setpoint. Other advanced control techniques such as model predictive control and economizer control were also implemented and tested, and more than 20% total energy saving was achieved.

DISTRIBUTED MODEL PREDICTIVE CONTROL FOR BUILDING HVAC SYSTEMS: A CASE STUDY

Research Assistant: Vamsi Putta

Principal Investigators: Professors Jim Braun and Jianghai Hu

ABSTRACT

Model based predictive control (MPC) is increasingly being seen as an attractive approach in controlling building HVAC systems. One advantage of the MPC approach is the ability to integrate weather forecast, occupancy information and utility price variations in determining the optimal HVAC operation. However, application to real world building HVAC systems is limited by the large number of controllable variables to be optimized at every time instance. To facilitate real life implementation, we formulate a distributed solution to the MPC problem. This formulation decouples and optimizes the problem in parallel at a zone level and combines the solution to obtain the required set points. Using simulations based on a medium size commercial building in Philadelphia, we estimate the savings in energy and time obtained from implementing the strategy. Results indicate that the near optimal solutions can be obtained at a fraction of the computational complexity of traditional MPC approaches. This research has practical implications in obtaining scalable near optimal supervisory control strategies for commercial building HVAC systems.

DEVELOPMENT OF PLUG&PLUG OPTIMAL CONTROL ALGORITHMS FOR SMALL COMMERCIAL BUILDINGS

Research Assistants: Donghun Kim

Principal Investigator: Professor Jim Braun

ABSTRACT

Very few advanced control algorithms have been developed for small commercial buildings that utilize rooftop units (RTUs) in open spaces, such as for retail stores (e.g., Walmart, Walgreens, etc.), restaurants and factories, due to practical difficulties such as the spatial comfort variations, significant disturbances, high sensor costs, and high cost of engineering site-specific solutions. The high cost of implementing optimal control features has been an impediment to successful market penetration. Our work is to develop and demonstrate plug-and-play optimal coordination of multiple RTUs. The goal is to minimize the time require to configure controls strategies in order to enable more cost effective control implementations for small commercial building applications. The approach includes an adaptive control strategy for learning system behavior with a lumped distrubance modeling approach. Overall assessments of cost savings are being performed.

WASTE HEAT RECOVERY OPTIONS IN LARGE GAS-TURBINE COMBINED POWER PLANTS

Research Assistants: Ularee Upathumchard

Principal Investigator: Professor Eckhard Groll

ABSTRACT

Study of power plant heat loss and how to utilize the waste heat energy further to other applications and systems in order to increase power plant efficiency. The case study of this research is a 700-MW natural gas combined cycle power plant, North Bangkok Power Plant, located in an urban area of Bangkok, Thailand. Analysis of heat loss in combustion, power generation process, lubrication system, and cooling system; is required as a primary to obtain waste heat recovery options. Design of applications dependents to the amount of heat loss from each system and its temperature. The thermal system options conducted in this research are of complex absorption chillers (Ammonia-Water and Lithium-Bromide, in comparison), Organic Rankine Cycle, and pre-heater equipments. Models are generated and simulated thermodynamically through Engineering Equation Solver (EES) to define heat transfer rate recovered from the power plant. After all, the result will be synthesized and evaluated in concern of environmental impacts and cost analysis towards sustainability concept. Furthermore, this research will be submitted as a proposal to the Electricity Generating Authority of Thailand (EGAT) for implementation. This is also going to be an example leading other power plants in Thailand to develop waste energy utilization as to improve plant efficiency and sustain the fuel resources in the future.

HIGH COP HEAT PUMPS FOR COMMERCIAL ENERGY APPLICATIONS

Research Assistant: Supriya Dharkar

Principal Investigator: Professors Eckhard. A. Groll, Kazuaki Yazawa

Sponsor: Cooling Technologies Research Center

ABSTRACT

Many commercial buildings, including data centers, hotels and hospitals, have a simultaneous heating and cooling demand depending on season, occupation and auxiliary equipment. Typically, the heat emitted by the electronic equipment in a data centers is not used but rejected to the environment. This heat could provide a potential for cost-effective and energy efficient operation of the buildings, if appropriately integrated. Heat pumps combined with thermal storage tanks result in a time-phase-shift of the heating and cooling production against the demand. The technical challenges are to find the optimum capacity of the storage tanks for a reasonable response of the time-dependent demands with minimum electricity. This approach can help reduce the amount of expensive chemical batteries with high penetrations of renewable power sources.

The COP of a heat pump varies depending on the required temperatures for the cooling and heating supplies. Storing pre-produced cooling energy is a key to minimize the investment for the cooling supply systems while using the rejected heat to cover the heating demand will increase overall building efficiency. An experimental breadboard test system has already been build and commissioned. Data collection will begin quickly for system performance testing.

Within the project scope, a performance analysis of the system will be conducted as a function of targeted temperatures by changing the flow rates of the storage fluids. The research will focus firstly on the case of varying target temperatures. A quasi steady-state analysis model is considered for shorter time periods to find the impact of changing the target temperature on system COP. Using the results of this analysis, storage tank minimization will be carried out. Then, waste heat recovery is plugged in. Finally, intermittent power sources are considered to achieve higher energy efficiency.

An experimental bread board system has been designed, constructed and commissioned. Experiments and theoretical analysis will be performed at different operating conditions as part of the proposed project based on these tasks:

1. Experiments for model validation: Experimental work will be performed using the existing bread board system at varying operating conditions that will be used to verify the model predictions.
2. COP analysis for demand cycles: Quasi steady-state models will be developed and validated to predict the system performance and match it to the building demand. The analysis will consider the dynamic heating and cooling demands and determine the COP as a function of time.

Thermal storage design: Minimize the hot and cold storages based on the existing demands. The thermal storage analysis will explore the addition of intermittent power sources, such as solar.

Waste heat from high power electronic equipment is recovered for boosting the COP of the system that provides heating and cooling, which are essential for commercial buildings. Intermittent renewable power source are considered to optimize the thermal storages.

OPTIMIZING THE CONTROL OF FREE COOLING AND THERMAL ENERGY STORAGE OPTIONS AT PURDUE

Research Assistant: Rita Jaramillo

Principal Investigators: Professors Jim Braun and Travis Horton

Sponsor: Purdue Facilities

ABSTRACT

With more than 150 buildings in operation, the largest of them requiring cooling even during the winter, Purdue campus in West Lafayette offers many opportunities for energy savings and increased operating efficiency through the implementation of free cooling technology and thermal energy storage (TES). Currently the cooling demand during the winter (an average of 6000 Refrigeration Tons) is supplied by electric or steam chillers at Wade Power Plant. The Northwest Chiller Plant (NWCP) provides additional cooling capacity during the summer. Therefore, the NWCP could also be operated in free cooling mode with the addition of a plate-frame heat exchanger piped in a parallel by-pass circuit with the chillers to allow the cooling towers cool the campus water when ambient wetbulb temperature is sufficiently low, reducing the use of the energy-consuming chillers. The energy savings obtained might be further increased through the implementation of TES.

By carrying out computational simulation of the system based on extensive historical operational data, this study aims to evaluate the performance characteristics and energy savings attainable through the inclusion of free cooling and TES. A control strategy will be also developed to achieve optimum performance of the whole chilled water production system (Wade Plant and the NWCP) operating throughout the year. The results of this project, which represents a partnership between Academics and Physical Facilities at Purdue, will include economic analysis and technical considerations to determine the feasibility of implementing free-cooling at NWCP. The methodology and control strategy developed will be a useful reference for the development of similar applications.

ECONOMETRIC MODELING AND OPTIMIZATION OF CHP OPERATIONS OF THE WADE POWER PLANT

Research Assistant: Sugirdhalakshmi Ramaraj

Principal Investigators: Professors Jim Braun and Travis Horton

ABSTRACT

The Wade power plant at Purdue University produces electricity and steam through cogeneration. The steam generated from the utility boilers is used for campus heating, power generation, chilled water production and in-plant auxiliary usage. The steam, which is distributed through a steam tunnel system at 125 PSIG and 15 PSIG, is the sole heating source for 13.5 million gross square feet of Purdue campus buildings. The electricity generated using two steam turbine driven generators and one diesel engine driven generator provides 30-50% of the electricity required to meet campus needs. The remainder of the electricity is purchased from the local electric utility and includes a real-time pricing component that varies with time. Chilled water is generated using four steam driven chillers and two electric chillers and is delivered through a closed water circulation loop in which 40-45 °F is distributed to campus to meet the time-varying cooling demand. Purdue's environmental footprint is significantly reduced as the result of cogeneration.

The goal of our project is to develop strategies and evaluate cost savings potential associated with optimal control of resources at the Wade facility to meet campus electricity, heating, and cooling demands subject to time-varying prices, loads, and environmental conditions. The work includes: 1) analysis and modeling of the chilled water, steam and electricity production and distribution systems at the Wade utility plant 2) improvement of operation strategies to satisfy the primary campus heating and cooling demand depending on the availability of the various assets 3) exploration of energy savings potential by managing the energy production and consumption. Through the use of a nonlinear optimization, the control of equipment capacities that minimize operating costs can be determined. The classic make-or-buy decision characteristics and economic viability relative to grid-based electricity and on-site boiler heating will be studied.

A BOUNDARY ELEMENT APPROACH FOR ASSESSING THE ACOUSTIC PERFORMANCE OF ROADSIDE NOISE BARRIERS

Research Assistants: Yiming Wang

Principal Investigator: Professor Kai Ming Li

ABSTRACT

The boundary element method (BEM) is a powerful computational technique, providing numerical solutions to a range of scientific and engineering problems. Instead of computing the whole outdoor domain, one only needs to analyze the boundary (road surface and barrier surface) with the BEM method. Our mission is to improve the technique and to develop a faster numerical algorithm when the BEM method is applied for the prediction of the acoustic performance of roadside noise barriers. Indoor experiments will be conducted to validate the computational scheme. The outcome of this research will bring more accurate and faster numerical methods for tackling outdoor acoustic scattering problems, which have applications in the noise barrier design, sonar and radar technologies, architectural design, and a number of other related fields in noise control technologies.

SOUND PROPAGATION THROUGH TURBULENT ATMOSPHERE

Research Assistants: Yuan Peng

Principal Investigator: Professor Kai Ming Li

ABSTRACT

How does sound propagate in complex atmosphere with turbulence? Capable approaches are studied in this research to achieve a more accurate prediction of sound fields in a realistic atmospheric condition. By introducing an approach known as the Parabolic Equation (PE) method, arbitrary sound speed profiles and locally reacting impedance conditions can be incorporated in the numerical analysis. With a good starting field, the PE method advances the computation of sound fields in the horizontal range. The numerical scheme allows the change in the environmental conditions at each range step. Turbulence profiles can thus be included in the modeling process. This research will lead to an improvement of in the prediction of sound fields which provides a solid basis for applications in noise control, acoustic detection and a means for an investigation of the effect of atmospheric turbulence on outdoor sound propagation.

ACOUSTICAL MODELING OF THE SOUND FIELD WITHIN A RIGID POROUS LAYER: THEORY AND EXPERIMENTS

Research Assistants: Bao Tong and Hongdan Tao

Principal Investigator: Professor Kai Ming Li

ABSTRACT

Multi-layered sound absorption materials enable greater control over the acoustical design of noise mitigation measures. An accurate model for individual materials as well as their interactions at layer interfaces is needed to facilitate the design and optimization process. Of particular interest is the acoustical characterization of rigid porous materials which are non-locally reacting (i.e., the acoustical behavior of the materials depend on the angle of incidence). Some examples of rigid porous materials include foam, fiberglass, and granular mediums. An efficient and stable numerical model based on asymptotic evaluation methods is suggested. The accuracy of the proposed scheme is comparable to those achieved using a wave-based integral approach across a wide range of frequencies and propagation geometries. The computational savings can be used to model more complex layered structures and/or improve the iterative search for material parameters (e.g., the propagation constant and bulk modulus). The initial analysis is limited to a single rigid porous layer situated above a semi-infinite backing layer.

Numerical simulations indicate that much larger variations in the sound field can be observed within the porous layer rather than the above-ground sound field. Validation for the proposed model is performed using below ground probe microphone measurements from an airborne source and an MLS data acquisition system. The increased sensitivity of the below ground measurements may provide the additional constraints needed for unique determination of material properties. These improved material properties can be used to enhance existing software for noise modeling. Some possible applications include noise barrier designs, building insulation, and/or urban planning.

THE USE OF EQUIVALENT SOURCE MODELS FOR REDUCED ORDER SIMULATION IN ROOM ACOUSTICS

Research Assistants: Yangfan Liu

Principal Investigator: Professor J. Stuart Bolton

ABSTRACT

It is important to be able to predict the sound fields in rooms for a number of reasons. For example, it is important to be able to predict the effect of a domestic room environment on the audio output of a flat screen television, or to be able to predict the impact of a noise control treatment in an industrial space. It is well known that the sound field in a room can be accurately predicted for a given source type and room surface boundary conditions (such as surface normal impedance) by using the Boundary Element Method. However, since this approach entails a complete discretization of all the room surfaces into elements that are small compared to a wavelength, it is usually impractically time-consuming, especially at high frequencies. For the purpose of decreasing the time required to make an accurate room acoustics prediction, an alternative approach based on the use of Equivalent Source Models (ESMs) has been developed in the current research: this new approach makes it possible to avoid numerical integrations on the boundary elements thus increasing the computational speed significantly. The method is based on decomposing the room sound field into a free-field component of the source (assumed known) and a room component that represents the effects of scattering from both the room's interior surfaces and the source itself (if it is significantly large: a large television, for example). The impedance boundary conditions on the room surfaces are used to estimate the parameters of the ESM which represents the room component of the total sound field. Along with a "traditional" ESM, in which monopoles are distributed outside the room region, a multipole ESM of arbitrary order was developed for this room acoustics application; it consists of monopoles, dipoles, quadrupoles, etc. It has been found, in principle and also through a two-dimensional simulation for a circular room, that the multipole ESM yields the benefits of a large feasible frequency range, a relatively low model order, and the possibility of balancing the prediction accuracy and the computational intensity flexibly by the choice of the highest source order included in the multipole model structure.

OPTIMIZATION OF MULTIPLE-LAYER MICROPERFORATED PANELS AS FUNCTIONAL ABSORBERS AND DUCT LINERS

Research Assistants: Nicholas Nakjoo Kim

Principal Investigator: Professor J. Stuart Bolton

Sponsor: 3M Corporation

ABSTRACT

The interest in the use of microperforated panels (MPP) has increased in recent years since it has been recognized to that they can be combined with air backings to create efficient, fiber-free sound absorbing materials. Here, the focus is on MPP's made by creating holes having diameters on the order of 100 microns in thin polymer films. The acoustical properties of MPP's depend on the hole diameter, the film thickness, the overall porosity of the perforated film, the film's mass per unit area, and the backing air cavity depth. These five parameters control the absorption peak location and the magnitude of the absorption coefficient (and the magnitude of the transmission loss in barrier applications). By an appropriate choice of these parameters good absorption performance can be achieve in a one or two octave band. That kind of solution may be adequate when it is necessary to control sound only in a specified frequency range (in the speech interference range, for example). However, in order to provide appropriate noise control solutions over a broader range of frequencies, it is necessary to design system featuring multiple-layers of MPP's, thus creating what amounts to a multi-degree-of-freedom system and so expanding the range over which good absorption can be obtained. In this research, two different situations were considered: one is a multiple-layer MPP to be used as a functional absorber, and the other is as a multi-layer cylindrical duct liner. Note that "Functional Absorber" is the name given to a system that can be hung, in an industrial space, for example, to provide acoustic absorption. The duct applications of interest would be in HVAC systems, whether in buildings, automotive systems or personal ventilators. In both applications, the focus was on obtaining the best possible performance in the full speech interference range, which spans the range from 500 Hz to 4000 kHz. In each case, a transfer matrix method has been developed to calculate the transmission loss and absorption coefficients provided by the systems. Note finally that the design of an N multiple-layer MPP system depends on $5N$ parameters, and so a general optimization becomes difficult in realistic cases when as many as ten layers might be used. Thus, the use of a genetic algorithm to optimize the system parameters has been adopted, since an algorithm of that sort can efficiently identify good solutions from a very large design space. The results, as presented in this poster, show that it is possible to identify the best combination of MPP's that improve the desired acoustic performance, whether absorption or transmission loss, in a prescribed frequency range.

APPLICATION-SCALE EXPERIMENTS ON HYBRID CELLULAR METAMATERIALS TO EVALUATE LOW FREQUENCY BARRIER PERFORMANCE

Research Assistants: Srinivas Varanasi

Principal Investigator: Professors J. Stuart Bolton and Thomas Seigmund

ABSTRACT

Conventional barrier materials require high mass per unit area to effectively block low frequency noise (below 1 kHz). High transmission loss metamaterials suggested to-date commonly require the introduction of relatively heavy resonating or constraining components which limit the applicability of these solutions in applications where it is desirable to minimize the treatment mass at a given transmission loss level. Here it is proposed that a panel consisting of an array of cellular structures can create a high transmission loss in a specified low frequency range without an undue mass penalty being incurred. The cellular acoustical metamaterial considered comprises a periodic arrangement of unit plates held in a grid-like frame. The effectiveness of these materials in blocking low frequency noise was studied through numerical simulations using a coupled acoustical-structural model of bench-top standing wave tube characterization setup.

To take the proposed concept to the next stage of commercialization, it is proposed to conduct validating experiments on cellular metamaterial panels with dimensions of 1.2m × 1.2m by using the intensity methods or the standard test methods prescribed. The test setup consists of a reverberation room, and a semi-anechoic termination with the cellular panel to be characterized placed at their interface. This test setup allows for characterization of the cellular panel performance for random incidence of sound which closely reflects the scenario of many real-life applications.

A series of samples with varying material contrast in the unit cell will be made based on the test cases studied numerically, and the proposed characterization tests will be conducted. The obtained results will be compared with the available numerical results for validation. As a next step, the cellular panels will be enhanced with sound absorbing microperforated foam material, and the tests done on cellular panels will be repeated. The purpose of the foam on the incident side is to refract the sound towards normal (due to low sound speed) to make the panel performance more or less independent of incidence angle. The purpose of the ultrafine fiber on the transmission side is to fill in the dips in the panel transmission loss. The test data from these tests can be evaluated for the improvement in performance achieved at the dips in STL.

EFFECTS OF COMPRESSION ON THE TRANSMISSION LOSS OF POROUS MATERIALS

Research Assistant: Edna Yang

Principal Investigator: Professors Stuart Bolton

ABSTRACT

In this research, how compression ratio will affect transmission loss of porous materials is modeled and tested. Johnson et. als' model of porous material is used for the theoretical prediction for the transmission loss change due to thickness change caused by compression. Instead of modeling the material with static frame equation, the limp equation is chosen due to that vibration of the fiber structure should not be neglected. The actual transmission loss of a particular type of glass wool is measured via impedance tube. Although some parameters needed for the theoretical prediction are not directly measured, they can be obtained through mathematical optimization based on the experimental data. The results of the research shows that transmission loss of porous material under deformation can be predicted using mathematical equations. It also provides an guideline for companies selling products that requires porous material to take transmission loss change into consideration at the designing stage. What's more, this results can be applied to porous material manufacturing industry to obtain same transmission loss quality with smaller amount of material.

THE RELATION OF VEHICLE ROAD NOISE TO TIRE DYNAMIC CHARACTERISTICS

Research Assistants: Nicholas Sakamoto

Principal Investigator: Professor J. Stuart Bolton

Sponsor: Ford Motor Company

ABSTRACT

The identification of the noise and vibration generation mechanisms of tire/road noise would permit the selection of tires that reduce vehicle pass-by noise, increase passenger comfort, and conform with manufacturer design specifications. It has been suggested that: (i) airborne sound radiation is primarily associated with waves propagating in the treadband at speeds greater than the speed of sound in air, and (ii) structure-borne components that transmit to the vehicle interior through the suspension are primarily associated with the appearance of the n=1 circumferential mode of the tire (since it is the only mode that, in principle, is capable of generating a net dynamic force at the wheel hub). The development of an off-vehicle, lab-based screening test that could be used to quantify those critical components would allow an automotive manufacturer to compare a variety of tires' noise and vibration characteristics without the expense and time required to perform on-vehicle road testing. The development of such a screening procedure is the objective of the current research.

Our current research therefore focuses on comparing airborne and structure-borne components measured by using the Tire Pavement Test Apparatus (TPTA) with tire dynamic characteristics measured independently. The TPTA allows tires to be run on realistic road surfaces in the lab at speeds up to 50 km/hr while measuring the sound radiated from the tire/road contact area and the vibration transmitted to the wheel hub; these measurements thus represent the noise and vibration levels that would typically be measured during a road test. The independent tire testing is performed by using a laser vibrometer to measure a stationary tire's point and transfer mobility around the tire circumference. A wave number transform is then applied to the latter data to quantify the number of waves propagating in the tire treadband and their speeds. To quantify the potential for airborne sound radiation, the magnitude of the supersonic components in the wave number transform are compared with the normalized sound intensity level measurements from the TPTA. As regards the structure-borne components, the n=1 contribution to the wave number spectrum versus frequency is compared with data from a triaxial accelerometer mounted on the tire's hub.

To-date, a sample set of tires from various tire manufacturers has been tested. The ranking of the tires' noise and vibration levels from experimental data suggests that a clear correlation exists between a tire's dynamic characteristics and its noise generating mechanisms, and it is therefore possible to assess a tire's potential for generating unacceptable levels of noise and vibration based on an in-laboratory test.

EFFECT OF ROTATION ON COUPLED TIRE STRUCTURAL-ACOUSTIC MODES

Research Assistants: Rui Cao

Principal Investigator: Professor J. Stuart Bolton

ABSTRACT

It is generally considered that acoustic modes exist in the air-filled space of an automotive tire, and that they are driven by motion at the tire/road contact patch. The first circumferential mode, in particular, is considered to be very important since it can apply a net transverse force to the wheel hub, and typically occurs around 200 Hz, a frequency component that can transmit effectively through automotive suspensions. Thus, the tire acoustic mode makes a significant contribution to structure-borne vehicle interior noise levels, and thus it is important to be able to model its characteristics in detail, including the effects of tire rotation, which is known to cause a frequency-splitting phenomenon to occur. The focus of the present research was to develop a fully-coupled structural-acoustic model of a rotating tire, so that the structural motion resulting from the "acoustic" modes could be identified along with the acoustic field that results from tire "structural" modes. Thus, the effect of rotation on coupled tire structural-acoustic modes has been examined in detail in this research. A simplified model of a tire, including both the internal and external airspace, has been used for this purpose. The tire is "unwrapped", so that the tire carcass can be modeled as a translating string, and periodic conditions are imposed on the string ends. The internal air space also translates with the tire while the external air space is modeled as being stationary. The three systems are coupled through appropriate displacement and dynamic boundary conditions. A characteristic equation can then be derived by combining the governing equation of the rotating tire structure, the acoustic wave equation in the translating fluid and boundary conditions. The characteristic equation can then be solved numerically to give the dispersive wave propagation characteristics of the coupled system. From the dispersion relations found in that way, the natural frequencies of the coupled structural-acoustic modes can be identified: some of those modes are essentially interior acoustic modes, while some are essentially structural modes. The new results give, in particular, the wave numbers of the coupled tire model at different translation speeds, and those results have been found to match well with experimental data. The pressure distribution within the airspace can be calculated, along with the natural frequencies, and both have been compared with the stationary case for both the structural mode and acoustical modes. It has been found, for example, that the "structural" modes are associated with a pressure field within the tire that decays rapidly from the tire surface towards the rim, while the first "acoustic" mode is associated with a sound pressure that is nearly independent of position across the width of the air-space. A clear frequency split phenomenon has also been identified. These results not only help to characterize and explain the acoustics of a spinning tire, but also facilitate an understanding of the impact of tire noise on vehicle interior and exterior noise.

In the future, the tire model will be improved by incorporating bending stiffness and curvature to achieve better alignment with the practical situation.

FAN NOISE CONTROL

Research Assistants: Seungkyu Lee

Principal Investigator: Professor J. Stuart Bolton

Sponsor: 3M Corporation

ABSTRACT

The noise radiated by electronic devices often results from the axial fans that are used to cool them. One component of axial fan noise is created by fluid shearing in the tip clearance region. In gas turbines, tip noise can be reduced by installing a finite flow resistance strip in the housing around the fan circumference. The finite level of flow resistance created by the slightly permeable housing may reduce turbulence levels in the tip region and so reduce the tip noise. In the present work, the housing of a 120 mm axial fan was modified to accommodate strips of microperforated materials. The fan performance with and without the microperforated treatment has been measured so that modified and unmodified fans could be operated as the same performance points, and acoustical testing was performed using the ISO 10302 plenum. The fan noise was quantified on the basis of the blade passage tone level. Tests were performed using microperforated materials spanning a range of flow resistances and the sound power level generated by the fan was measured by using the method described on ISO 3744. It has been found that there are areas in the fan performance map where tonal noise levels can be consistently reduced by the use of a microperforated housing element. Tradeoffs between noise reductions and the performance of the fans will be suggested based on the results of this study. Furthermore, it is expected that the results of the work can provide guidelines for design treatments that can be integrated into typical fan designs to create a new generation of reduced-noise cooling fans.

ASSESSMENT OF NOISE METRICS FOR APPLICATION TO LARGE CIVIL TILT ROTOR FLIGHT OPERATIONS

Research Assistant: Andrew McMullen

Principal Investigator: Professor Patricia Davies

Sponsor: NASA

ABSTRACT

Metrics currently in use to assess impact of aircraft noise, typically l annoyance, need improvement. Also, currently used aircraft noise metrics were developed based, mostly, on community responses to fixed wing aircraft noise, and may not be as effective for assessment of noise generated by rotorcraft, such as the proposed large civil tilt rotorcraft (LCTR) because noise generated by rotorcraft is different to noise generated by conventional fixed-wing aircraft. Rotorcraft noise can include strong tonal components, fluctuations, and a higher level of low frequency noise. Due to these differences, the effectiveness of aircraft noise metrics to predict human response to rotorcraft noise needs to be examined. The research includes: (1) identification of perceived rotorcraft noise characteristics, (2) quantification of those characteristics, (3) development of signal manipulation and simulation methodologies to enhance or attenuate those characteristics and (4) development of annoyance models. Two psychoacoustics tests were performed to identify sounds characteristics of importance. First earphones were used for playback of 20 rotorcraft sounds with subjects in a sound booth, and then a similar test was conducted using loudspeakers with subjects in a more natural setting. Nineteen sound characteristic scales were developed and subjects were asked to make judgments on these scales. Analysis revealed that there are up to five factors present in the response data and these are related to loudness, signal irregularity, roughness, spectral balance and tonality. The sound simulation tool is being developed so that these sound attributes can be varied independently; this will allow us to examine, through future tests with subjects, how each characteristic impacts annoyance judgments, a necessary step in the development of an annoyance metric. Metrics that relate noise to human responses are important to the design of mechanical devices and systems. Noise metrics together with source and propagation models are used to predict the effects of aircraft noise on communities. Airports use this information to restructure aircraft activity so that the noise effect on the surrounding community is decreased. Similarly, aircraft engineers use the metrics with sound prediction tools to optimize their aircraft designs.

DEVELOPMENT OF SOUND QUALITY METRICS FOR DIESEL ENGINE COMPONENT SPECIFICATION

Research Assistants: Brandon Sobecki

Principal Investigator: Professors Patricia Davies and J. Stuart Bolton

Sponsor: Cummins Inc.

ABSTRACT

Sound quality is an important factor in the design of competitive diesel engines. The noise produced by specific components and mechanisms in the engine can play a significant role in determining the perceived quality of the overall noise. The goal of the present research is to characterize the sounds produced by the two phenomena known as gear rattle and combustion clatter in order to develop a model that can be used to assess their level in a way that connects directly with human perception. Most previous work in this area has been focused on rating the overall sound quality of diesel engines, but little has been done to develop models of perception of rattle and clatter noise, in particular. A database of various gear rattle and combustion clatter sounds will be compiled in conjunction with personnel from Cummins. Signal analysis, including the calculation of commonly used diesel engine sound quality metrics, will be used to develop methods to vary relative levels of sound attributes for use in sound quality testing. A series of psychoacoustic tests will then be performed in order to identify and characterize perceived attributes of gear rattle and combustion clatter noise and to understand how these attributes relate to annoyance. We will also compare the responses of people who work on diesel engines with those of a more general population. The outcome of this research will be a method to predict how people perceive gear rattle and combustion clatter noise so that Cummins can set component noise targets directly related to human perception. When coupled with noise generation predictions, this approach can be used to optimize the quality of the component noise.

IMPROVEMENTS TO MODELS OF FLEXIBLE POLYURETHANE FOAM TO ENHANCE PREDICTIONS OF SEAT-OCCUPANT DYNAMICS

Research Assistant: Yousof Azizi

Principal Investigator: Professors Anil Bajaj and Patricia Davies

ABSTRACT

Vehicle occupants are exposed to low frequency vibration that can cause fatigue, lower back pain, spine injuries, and etc. Understanding the behavior of a seat-occupant system is important in order to minimize these harmful vibrations. The behavior of a seat-occupant system is mainly affected by the properties of seating foam which exhibits nonlinear viscoelastic behavior. Therefore, understanding the foam-occupant interaction and the way foam properties affect the response of the occupant is essential in modeling of a seat-occupant system. In order to understand the role of flexible polyurethane foam in the complex seat-occupant system, the response of a single-degree-of-freedom foam-mass system, which is also the simplest model representing a seat-occupant system, was studied. Three different nonlinear viscoelastic foam models with real system parameters, which were previously estimated using a set of slow cyclic compression tests on a seating foam sample, were used to develop the governing equations of the single-degree of freedom foam-mass system. The incremental harmonic balance method was then used to determine the steady-state behavior of the system subjected to harmonic base excitation at different levels and frequencies. This method was especially used to reduce the time required to generate the steady-state response at the driving frequency and at harmonics of the driving frequency from that required when using direct time-integration of the governing equations to determine the steady state response. Using this method, the effects of different viscoelastic models, parameters, riding masses, base excitation levels and damping coefficients on the response were investigated. Finally, a set of tests was conducted by applying base excitation to an experimental single-degree of freedom foam-mass system using an especially designed set-up to verify the results obtained from simulating the model. It was observed that the results from the simulation match the experimental results after introducing some modifications to the model.

MODELING AND SYSTEM IDENTIFICATION OF STRUCTURAL SYSTEMS INCORPORATING NONLINEAR VISCOELASTIC MATERIALS

Research Assistant: Udbhau Bhattiprolu

Principal Investigators: Anil Bajaj and Patricia Davies

Sponsor: Partially sponsored by the National Science Foundation

ABSTRACT

Muscle tissue, skin and several other biomaterials used in the biomedical industry as well as flexible polyurethane foams used for cushioning in the furniture and automotive industries, all exhibit nonlinear viscoelastic behavior. To design systems that incorporate these materials, it is important to be able to model their mechanical behavior and thus be able to predict the dynamic response of the systems. Because of the nonlinear and memory (viscoelastic) properties of the materials, this is a challenging research area. The results and understanding developed here for a pinned-pinned beam on a foam foundation interacting with flexible polyurethane foams should be applicable to more complicated systems incorporating many of the materials mentioned above. The approach to modeling is to start with linear models of the foam, gradually increase the complexity by incorporating, in stages, elastic nonlinearity and then viscoelasticity. Unlike most of the studies reported in the literature, the foam foundation was assumed to react only in compression to encapsulate a wider range of problems seen in practical applications. Thus the model has to be equipped with the ability to predict the changing contact length – this makes the modeling and analysis even much more challenging. An experiment is being designed to verify the applicability of the model and initially, harmonic excitation of the system is being studied. The model will then be used to determine the geometry and materials in the experimental system and the excitation requirements. In the near future, a system identification procedure will be developed based on the model structure and the types of excitation that are feasible in the experiment. The procedure will be applied to the experimental system and the range of the applicability of the resulting model will be explored. The system identification approach and simulations of various model structures will be used to extend the capability of the beam-foam system model to predict responses observed in experiments under a wider variety of loading conditions and excitation levels. The approach to modeling structures interacting with nonlinear viscoelastic materials can be applied to many engineering systems, for example those incorporating rubber-like materials.

THERMAL AND MECHANICAL RESPONSE OF PARTICULATE COMPOSITE PLATES UNDER INERTIAL EXCITATION

Research Assistants: Jacob K. Miller, Daniel C. Woods

Principal Investigator: Professor Jeffrey F. Rhoads

ABSTRACT

Some of the greatest threats to the Armed Forces of the United States are improvised explosive devices (IEDs), which typically consist of disguised homemade explosive charges, a mechanical structure, and associated electronics. Despite the significant amount of IED-related research that has been conducted in recent years, no unilaterally effective and mass-deployable detection and defeat mechanism has been developed to date. The current research effort seeks to examine the utility of electromagnetic and acoustic excitations in stand-off detection systems. Due to the vapor pressure characteristics of composite explosives, even a small temperature rise may lead to an outgassing of detectable vapors. Targeting this phenomenon, the aim of this project is to elicit a thermal response within various energetic materials to enhance stand-off vapor detection. Specifically, the work seeks to develop and evaluate various experimental methodologies for pumping large amounts of energy into shielded energetic materials of arbitrary geometries using carefully-shaped acoustic and electromagnetic excitation signals. To this end, the macroscopic vibratory response of plates formed from surrogate energetic materials is characterized, with the frequency responses and operational deflection shapes presented for HTPB-based rectangular plates with varying crystal/binder ratios. Infrared thermal imaging is utilized to record the temperature response of the plates, and comparisons are made to thermal and mechanical results obtained from a first-principles analytical plate model.

IDENTIFICATION OF LOW FREQUENCY DYNAMIC BEHAVIOR OF SURROGATE EXPLOSIVE MATERIALS

Research Assistants: Jelena Paripovic

Principal Investigator: Professor Patricia Davies

Sponsor: DOD – Semiwave Multi-University Research Initiative

ABSTRACT

The mechanical response of energetic materials, especially those used in improvised explosive devices, is of great interest in the defense community. By understanding the mechanical behavior of the explosive material, it is believed that a remote acoustic or electromagnetic excitation may be tuned to produce signatures that can be used to indicate the presence of explosives. This is one of a group of projects focused on this issue. The goal of this particular project is to develop robust models of the low frequency uniaxial behavior of surrogate polymer energetic materials. The material used in the research is hydroxyl-terminated polybutadiene (HTPB) binder embedded with ammonium chloride crystals (NH_4Cl), which is very similar in structure to the types of explosive materials of interest. An experimental rig consisting of a mass attached to a block of the material constrained to move along one axis was designed and constructed. By attaching this rig to an electro-dynamic shaker, a series of base-excitation tests have been conducted with both 0% and with 50% crystal/binder volume fraction materials. The repeatability of the experiments within one day and over several months has been examined. Within one day, experiments are highly repeatable for both volume fractions, but over time the position of the 50% material's resonance of the system shifts to the right and appears to harden while the 0% material remains repeatable. The behavior of the 0% material is approximately linear: increased excitation leads to a proportionally increased response, while the 50% material's frequency response changes shape with increased excitation indicating either a softening of the material or an increase in the damping of the material, or both. A continuous-time system identification approach is being used in the development of models that predict the mass-material system's dynamic response. Various linear, nonlinear and viscoelastic models have been fitted to the experimental data. Some slight improvement in performance, over that of a simple linear mass-spring-damper model, was found when a nonlinear stiffness term was included. Including a one-term hereditary viscoelastic term was necessary to fully capture the frequency response function shapes. However, it was not possible, with the model structures examined, to predict the frequency response amplitudes at different base excitation levels with a single model. The system identification procedure is currently being adapted to allow for estimation of more complicated nonlinear viscoelastic and damping terms. This research will provide an important step in the development of a global model that can relate stress, strain, temperature and strain-rate for the types of materials used in improvised explosive devises. The models developed and estimated material properties are being shared with the researchers in the other projects who are studying other systems that incorporate these surrogate materials.

STRUCTURAL DYNAMIC IMAGING THROUGH INTERFACES

Research Assistants: Christopher Watson

Principal Investigator: Professors Douglas E. Adams and Jeffrey F. Rhoads

Sponsor: Office of Naval Research

ABSTRACT

In many engineering applications, diagnostic techniques are needed to characterize the mechanical properties of internal components that are not readily visible at the surface of an object. Understanding the role of structural interfaces between two bodies is a necessary prerequisite to developing these diagnostic techniques because the mechanical and geometric properties of the interface determine the degree to which surface measurements can be used to interrogate sub-surface components.

In this work, vibration measurements on a polycarbonate buffer material are used to distinguish and characterize the mechanical properties of a polymeric, particulate composite target material located beneath the buffer. A three-dimensional laser Doppler vibrometer and piezoelectric inertial actuator are used to measure the broadband response of the two-body structural dynamic system. Because of the importance of the actuator dynamics to the diagnostic measurements, a descriptive model is developed to better understand these dynamics and interpret the results. The longitudinal dynamics of the two-body system are shown to involve stronger coupling between the buffer and target materials as compared to the transverse dynamics. Changes in the surface velocity of the buffer material are also studied as a function of the volume fraction of crystals in the target composite material, a key mechanical property, as well as the nature of the bonding at the interface between the two materials. It is demonstrated that both the linear and nonlinear vibration characteristics of the buffer material change as a function of the composition of the target material as well as the interface bond type, suggesting that, given enough understanding of the interface bond type, a compositional diagnostic procedure is possible using surface vibration measurements.

NEAR-FIELD PRESSURE DISTRIBUTIONS TO ENHANCE SOUND TRANSMISSION INTO MULTI-LAYER MATERIALS

Research Assistant: Andrew M. Jessop

Principal Investigator: Prof. J. Stuart Bolton

ABSTRACT

The SEMIWAVE MURI, a multi-university research initiative, is focused on large-standoff excitation of energetic materials. Other groups are looking at the coupling between vibration and detectability of the energetic; the focus of this research is to provide an acoustical means of vibration instigation.

The large difference in both density and wave speed between air and most solids prevents significant energy transfer from incident acoustic waves across the air-material interface. The wave speed difference also causes refraction, wherein the energy transmitted into the material does not propagate as effectively into the material. By utilizing evanescent pressure distributions, which decay normal to the usual direction of propagation and are represented as plane waves propagating with complex angles, energy propagation through the interface can be increased at incident angles where waves typically do not propagate into a material with any effectiveness. By using an array of sources, it is possible to produce evanescent pressure distributions in the solid. Parameters related to both the incident wave and the array geometry would affect the ability of the array to generate the desired pressure distributions.

The energetics of interest are typically comprised of multiple layers, including high-density boundary materials that may impede energy propagation into the energetic. A model is developed that gives a full accounting of material states in the multi-layer model, including the calculation of intensity, in fluid-solid systems. By using wavenumber-frequency analysis, we can target specific components in the multi-layer system and understand wave types that cause energy propagation into the system.

MODAL ANALYSIS AND LOAD IDENTIFICATION TECHNIQUES FOR A RAPIDLY EMPLACED BRIDGE SYSTEM

Research Assistants: Christian Silva

Principal Investigator: Professor Shirley Dyke

Sponsor: Army Corp of Engineers

ABSTRACT

This project's goals are: 1) To determine through experimental procedures the vibration behavior of a military-type lightweight bridge under various types of loading conditions, namely impact loading; vehicles travelling along the bridge at different speeds; and environment noise. 2) To develop a valid approach to identify the type of loading the bridge is subjected to from experimental data only.

To accomplish such goals, a team from Purdue University's Intelligent Infrastructure Systems Lab travelled to Virginia to visit a real structure site where preliminary tests were conducted. Among these tests were obtaining good measurements of the structure to construct a realistic finite element mode, and to perform real testing with the aid of appropriate instrumentation for obtaining vibration data.

The finite element model is intended to be the reference structure, since no information regarding similar bridges has been found in bibliography. Therefore, the only reference available is a computational model as close as possible to the real bridge. After obtaining a Finite Element Model simulation which will lead to analytical results which can be further compared and therefore validated with experimental data in terms of natural frequencies damping ratios and mode shapes.

The second goal of the project is to assess, through modal identification techniques, if the analytical results previously determined are in concordance with the experimental results. For this stage, several tests will be conducted in the real structure. 1) Impact testing. This consists in imposing a controlled input to the structure with a modally tuned hammer, and to gather the response of the structure by means of piezo-electric accelerometers placed in previously determined locations of the structure. An adequate data acquisition system will be used for this task and data will be gathered using two sampling frequencies, 1024Hz and 4096Hz for comparison purposes and to make sure no information is lost due to lack of sampling frequency. 2) Vehicle loading testing. This testing will be conducted using a real vehicle crossing across the structure. Three speeds will be used (slow, medium and fast) to assess the response of the bridge to a suddenly applied load/unload with a finite dwell time. The results of these tests will be used primarily in developing a counting algorithm capable of determining the number of crossings across the bridge for each type of vehicle, with type. In other words, to analyze the relationship between the bridge and the loads it can withstand.

The ultimate objective would be to determine with considerable accuracy the type of vehicle crossing the bridge (related to its mass), as well as the amount of vehicles that have crossed a determined bridge throughout its usable lifespan.

VISION BASED STRUCTURAL FAULTS DETECTION

Research Assistants: Chul Yeum

Principal Investigator: Professor Shirley Dyke

ABSTRACT

This study presents a new concept of visual inspection techniques for large-scale bridge structures. Visual inspection is the one of predominant nondestructive testing method used to identify the specific types of faults on bridges such as crack, corrosion, or deformation. However, current methods demand long inspection time to cover large areas of bridges, and highly rely on inspector's subjective or empirical knowledge of damage on bridges. To address these limitations, an image based visual inspection technique is proposed, which include fully automated image acquisition, image classification, damage detection, and localization. First, aerial cameras gather images of the bridge similar to what inspectors see for inspection. Next, inspectors decide regions of interest (ROI) from some of images, which are susceptible to get damage, for example, connecting joints or bolts. Then, image filters are designed to extract ROIs from all acquired images. Once ROIs are obtained, visual damage in ROIs will be identified using image processing techniques. Since the image processing techniques for damage detection can be designed by expert inspectors in the first time and use them in the later inspection, inspection results are robust and accurate rather than the one from individual inspection.

MODEL-BASED OPTIMIZATION OF HEAVY-DUTY HYBRID ELECTRIC POWERTRAINS

Research Assistants: Xing Jin, Ashish Vora

Principal Investigator: Professor Greg Shaver

Sponsor: DOE, Cummins Inc.

ABSTRACT

Electrification of heavy-duty powertrains presents immense opportunities for reducing fuel consumption and associated emissions, which is required to meet increasingly stringent regulations in this domain. The challenge (and opportunity) with powertrain electrification lies in the diversity of applications in the heavy-duty vehicle domain. A model-based approach can thus enable a systematic and efficient exploration of the design space for diverse applications from a design and control perspective. This study aims to explore system performance vs. cost trade-offs using parametric dynamic models and robust design optimization. Design of Experiments is utilized to setup parametric simulation studies on the powertrain simulation software Autonomie. Regression modeling is used to capture the impact of component-level and system-level design and control parameters on system-level metrics such as fuel consumption, system cost, criteria emissions and critical component life. Robust optimization techniques are then utilized to achieve an optimal design for a specific application. This project ultimately aims to create a reconfigurable powertrain simulation model that can be reused across various hybrid architectures and components with models of varying complexity based on the optimization objectives. Thus this model and methodology can be used to achieve optimization in the component as well as system domains with the use of appropriate parametric models.

ESTIMATION AND COMPENSATION OF FUEL QUANTITY VARIATION IN MULTIPULSE INJECTIONS

Research Assistants: Shambhavi Balasubramanian and Sai Shirsikar

Principal Investigator: Professor Peter Meckl

ABSTRACT

Increasingly stringent emission norms has been one of the major driving forces behind the research in diesel engines for more innovative combustion strategies, after-treatment techniques and fuel injection systems. Multiple pulse injection strategies have been investigated to limit exhaust emissions, noise and fuel consumption.

Though multiple-pulse injection strategies are advantageous, they are challenging to monitor and control. The fueling provided by individual pulses in multiple-pulse injections differs from that generated by single injection pulses. Thus, estimation and control strategies for single-pulse injection are insufficient for multiple-pulse injection cases. To compensate for the fueling variation, the first step is to estimate the fueling for the given case of multi-pulse injections.

After the first pulse is injected, pressure waves are set up inside the injector body. This changes the initial conditions for the next injection. The current study focuses on the effect of these body pressure fluctuations to estimate the fueling variation in two-pulse cases. A hybrid modeling approach is followed to come up with a simple model for the lower body of the injector to estimate the mass flow rate and fueling. The model is calibrated using an optimization technique to come up with a set of coefficients defining the given injector configuration using a set of simulated single-pulse injection cases. These coefficients are implemented to estimate the fueling and calculate the fueling variation for the second pulse of a two-pulse case by using a simulated body pressure signal. The results of the technique are discussed for a number of rail pressure, commanded on-time and hydraulic separation values.

The injectors under study belong to the family of Cummins Scania XPI injectors. These are solenoid actuated, high pressure injectors. The work is sponsored by Cummins Fuel Systems, Columbus, Indiana.

OPTIMAL CONTROL OF NO_x REDUCING CATALYST BASED ON NO_x AND NH_3 SENSOR FEEDBACK CONTROL STRATEGY AND ELECTRICALLY HEATED CATALYSTS ON A DIESEL HYBRID PLATFORM

Research Assistant: Jagdish Hiremath

Principal Investigator: Professor Peter Meckl

ABSTRACT

The SCR-Ammonia Technology is increasingly being seen as a critical pollution control technology in the current and future diesel based automotive applications specifically for NO_X control. Apart from the catalyst, the SCR-Ammonia system also consists of a Urea Doser unit responsible for accurate metering and dosing of the urea solution in the exhaust stream and is governed by a sophisticated control system taking various sensor inputs from engine and exhaust stream while at the same time estimating the NH_3 stored on the catalyst. However, excess unreacted ammonia (produced in-situ from urea), which is the primary reducing agent for NO_X, itself is a hazardous environment pollutant. This system hence poses a challenge not only in terms of designing an efficient and robust urea dosing control system to maintain the delicate NO_X-NH_3 balance, but also in ensuring reasonable performance of the catalyst in real life duty cycles and environments for commercial vehicles.

The following poster illustrates some concepts being researched and developed to address the challenges highlighted above and are based on active NH3 sensor feedback (in addition to the already available NOX sensor values). Concepts such as real time NH3 storage estimation based on multi-sensor data, Urea --> NH3 conversion monitor for dosing control and downstream NH3 sensor feedback based dosing control are presented. In addition to the control strategies, electrical heating of catalysts exploiting the presence of an electric supply onboard has been considered as a measure to mitigate the high emissions at cold start conditions attributed primarily to insufficient catalyst activity at low temperatures.

NO/NO_2 RATIO FOR A DIESEL OXIDATION CATALYST BASED ON LIGHT-OFF TEMPERATURE

Research Assistants: Prateek Tayal

Principal Investigator: Professor Peter Meckl

ABSTRACT

Among its many functions, the diesel oxidation catalyst (DOC) is responsible for oxidizing hydrocarbons and carbon monoxide in the exhaust stream into H2O and CO2. It is also responsible for oxidizing NO into NO2. This conversion serves two purposes: 1) it allows diesel particulate filter (DPF) regeneration at a lower temperature, and 2) it provides feed gas for selective catalytic reduction (SCR) so that NOx can be effectively removed at a lower temperature. As is true with many catalyzed filters, the DOC thermally ages as it operates, which causes the oxidation of NO (and the rest of the reactions in the DOC) to become less efficient, which naturally leads to reduced concentrations of NO2. In the SCR system, the lower concentration of NO2 means that higher temperatures are required to effectively reduce NOx and/or different urea dosing is required as compared to the healthy DOC case.

Aging in the DOC can be detected with shifts in the light-off temperature at which hydrocarbons are converted. The light-off temperature is the temperature at which the efficiency of hydrocarbon conversion exceeds 50%. As a DOC ages, its light-off temperature will increase. It thus becomes a potential indicator of oxidation efficiency, thereby providing a mechanism to estimate NO/NO2 ratio as feedgas to the SCR system.

This project aims to develop a model of the DOC that will connect light-off temperature to NO/NO2 ratio. Once light-off temperatures have been determined for several degrees of aging, and the corresponding NO/NO2 ratios have been determined, appropriate models for estimating NO/NO2 ratio as function of light-off temperature will be developed. These models will be hybrids of physics-based and data-based models. Once models have been obtained, they will be validated on experimental data on a 6.7L ISB series engine.

PARAMETER ESTIMATION AND RATE SHAPING CONTROL OF A PIEZOELECTRIC FUEL INJECTOR

Research Assistants: Bradley Pietrzak and Dat Duc Le

Principal Investigator: Professor Greg Shaver

ABSTRACT

In vehicles that use internal combustion (IC) engines, several factors contribute the vehicle's overall fuel economy and the harmful emissions that are found in its exhaust. The fuel injection system used in an IC engine is a key contributor to both of these things. While most fuel injectors in use today largely operate in a fully-on or fully-off state, current research suggests that injecting certain amounts of fuel during certain time periods of an engine cycle can improve fuel economy while reducing NOx and particulate matter emissions. Such fuel injections are said to be "rate-shaped," and creating them requires advancements in injector technology. In this work, a piezoelectrically actuated fuel injector with very fast response times is used to produce rate-shaped injection events.

In this project, a dynamic nonlinear model of the piezoelectric injector has been designed and experimentally validated using the injector test rig at Purdue. Additionally, a model-based estimator has been designed which can provide an estimate of the rate of fuel flowing out of the injector every six microseconds, which is useful because no such measurement is available on-engine. Using this estimator as feedback, a closed loop controller has been designed to ensure that the injector system can track a desired fuel flow rate-shape. Also, since several parameters of the injector model can vary from injector-to-injector and with injector ageing, recent effort has been made to use the flow rate estimator in combination with certain on-engine measurements to estimate a few important model parameters online. To validate this work, the injector model has been simulated in Matlab, and the control and estimation algorithms have been implemented on an NI CompactRIO FPGA.

IMPLEMENTATION AND PERFORMANCE UPDATE OF ECOCAR 2: PLUGGING INTO FUTURE

Research Assistants: Bilwa Jadhav, Brad Pietrzak, Leighton Roberts, Lucius Wang and Ashish Vora

Principal Investigator: Professor Greg Shaver

ABSTRACT

EcoCAR 2: Plugging into the Future, is a three-year collegiate engineering competition. The first year focuses on design and simulations that will intend to meet the required target, in-vehicle complete integration in the second year, and this being the third year, emphasizes on refinement and optimization. This competition is established by the U.S. Department of Energy (DOE) and General Motors (GM), and challenges to reduce the environmental impact of a Chevrolet Malibu without compromising its performance, safety and consumer acceptability. EcoCAR 2 requires the students to explore a variety of powertrain architectures focusing on electric drive vehicle technology. The teams utilize a 2013 Chevrolet Malibu, donated by General Motors as the integration platform for their advanced vehicle design. During the three years, EcoCAR 2 teams follow a real-world Vehicle Development Process (VDP) modeled after GM's VDP which serves as a roadmap for the engineering process of designing, building and refining their advanced technology vehicles. The main goals of this competition are, to reduce the overall fuel consumption, reduce the well-to-wheel greenhouse gas emissions, to reduce the tailpipe emissions while simultaneously maintaining the consumer acceptability in terms of vehicle performance, utility and safety.

The Purdue University EcoCAR team follows the parallel-through-the road (PTTR) plug-in hybrid vehicle architecture. This pairs an engine powering the front wheels of the vehicle with an electric motor powering the rear wheels. This arrangement gives the flexibility of being able to operate the vehicle in an all-electric mode, an all biodiesel mode, or a combination of both to create maximum power. For this functionality, a 1.7 L CIDI engine running on biodiesel, powering the front wheels and a 103 kW Magna motor powering the rear wheels is used. In order to power the motor, a high voltage (HV) energy storage system (ESS) is designed and integrated into the vehicle. The goal for the mechanical design of the ESS was to create a structure that will enclose all of the batteries and battery control modules to protect them from environmental factors and to prevent them from becoming displaced in the event of a collision. The enclosure will also serve as a means to isolate the consumer from the dangers of HV. The mechanical design deployed a cooling system that keeps the batteries operating in an acceptable temperature range while they are charging and discharging. The electrical design focused on harnessing a HV system that will adequately supply enough current in order to meet the peak loading condition, and yet be able to disconnect should a fault occur, to prevent component damage. The system was designed keeping safety in mind. Controllers will constantly be monitoring both the HV and LV systems to make sure that each is isolated from the other. Should a controller detect a problem, it will disconnect the HV system.

With research showing the alarming rate of increase in global warming and thus causing dangerous instabilities in the weather, a strong push has been initiated to reduce greenhouse gas emissions. Transportation being one of the top offenders in greenhouse gas emission has led to drive for improving the efficiency of the modern automobile. One of the current, biggest strategies in reducing the emissions produced by the transportation sector is to create a hybrid vehicle that is powered from both a fuel, such as gasoline, diesel, or hydrogen, and electricity. This merger has proven to be effective at decreasing harmful emissions such as carbon dioxide (CO_2) and nitrous oxides (NO_x) while also increasing fuel economy.

IMPROVING EFFICIENCY AND EMISSIONS CONTROL THROUGH VARIABLE VALVE ACTUATION ON A DIESEL ENGINE

Research Assistants: Chuan Ding, Mark Magee, Aswin Ramesh, Leighton Roberts

Principal Investigator: Professor Greg Shaver

Sponsors: Cummins Inc and Eaton Corporation

Abstract

To meet consumer demands for improved fuel economy as well as stringent emission regulations, engine manufacturers have begun to investigate the benefits of variable valve actuation systems. This study focuses on the quantification of the effects of varying valve timing events and optimization to achieve improved engine efficiency and hotter exhaust gas. Exhaust after treatment systems clean the harmful emissions from the exhaust gas; however, to be most effective, they must be maintained within a certain temperature range. Therefore, using variable valve actuation (VVA) to raise exhaust temperatures can assist in the control of emissions. Characterization of the valve modulation effects mentioned above is being performed both analytically with computational engine model simulations and experimentally with a fully variable valve actuation system implemented on a diesel engine. The experimental testbed is a 2010 Cummins ISB 6.7L engine with almost exclusively stock hardware (stock pistons, injectors/nozzles, turbocharger, etc.). A very unique capability of this multi-cylinder testbed is that it is outfitted with a fully-flexible electro-hydraulic variable valve actuation (VVA) system that enables cylinder-independent and cycle-to-cycle control of both the intake and exhaust valve events. Results from this study have shown that by modulating the intake and exhaust valve events, the combustion and gas exchange processes of the engine are directly affected, and depending on the change, improvements on emissions or fuel economy or both are possible. For example, by modulating the intake valve closing timing in a cycle, the work required to compress the gas can decrease while maintain the work output from combustion, thus improving the overall efficiency. This also leads to less fresh air intake, raising the temperature of combustion and the exhaust gas. Also, it been verified that by opening the exhaust valve early, more hot exhaust gases are released into the tail pipe raising the temperature seen at the after treatment system. In addition to raising exhaust temperature, trapping or re-inducting burned gases with certain valve events are being investigated to reduce emissions. Lastly, in a standard drive cycle, the engine operates at part load conditions for a significant portion of the cycle. Under these conditions, it is not often required that all cylinders are firing. By deactivating several cylinders, fuel economy benefits have been seen as well as an increase tailpipe temperature which can lead to after treatment performance. Knowledge of how VVA can improve efficiency and after-treatment systems will help make the operation of diesel engines cost less and emit less harmful gases into the environment.

OPERATING RANGE EXPANSION OF PREMIXED CHARGE COMPRESSION-IGNITED COMBUSTION IN A MULTI-CYLINDER DIESEL ENGINE WITH FLEXIBLE VALVE ACTUATION AND VARIABLE FUEL REACTIVITY

Research Assistants: Lucius Wang, David Fain, Mayura Halbe

Principal Investigator: Professor Greg Shaver

ABSTRACT

Pre-mixed charge compression ignition (PCCI) is an important advanced combustion strategy that may become a solution to the more stringent emissions requirements without much use of the complex and expensive aftertreatment systems. PCCI also helps improve the fuel economy by reducing the fuel consumption.

In order to understand why PCCI can only be used to a limited portion of the speed-load map, an extensive analytical and experimental analysis is conducted. Several important emission and efficiency parameters, such as NOx, PM, UHC, and CO emission, fuel efficiency, equivalence ratio, combustion noise, and combustion stability, are examined.

The characterization of PCCI operating space on mid-sized diesel engine provides insight to the limiting factors of PCCI, what can be done to improve those limitations, while also providing a map of where PCCI can currently be utilized.