THERMAL SYSTEMS RESEARCH

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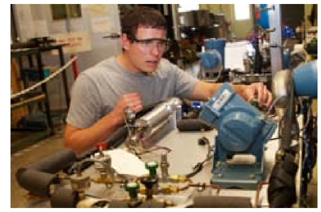
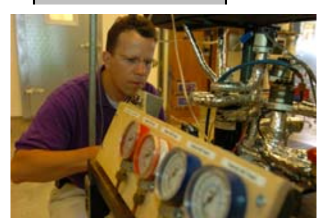
Thermal Systems Research Focus

From its beginning in the late 1950's to the present day, research in the areas of thermodynamics, heat transfer and fluid mechanics (thermal systems) has been an integral part of the Herrick Laboratories. Primarily this research has been in cooperation with the heating, ventilating, air-conditioning and refrigerating (HVAC&R) industries. Since 1958, over 300 students (approximately one-third at the doctoral level) have earned advanced degrees through their research in HVAC&R. Early work in the areas of heat transfer and thermophysical properties was geared towards improving the efficiency of equipment. Over time, equipment research evolved to include issues of product cost, reliability, comfort, noise and vibration. With the advent of high-speed digital computers, the focus of much of the work changed to *mathematical modeling and simulation*, including *computer-aided design* (CAD) and computerized design *optimization procedures.* The development of computer simulation tools not only improved the capabilities for equipment design and analysis, but has also provided practical methods for designing and analyzing complete systems.



During the energy shortages of the 1970s, *energy utilization* became a focus of the research programs. Illumination, heating and cooling of space, water heating and refrigeration in residential, commercial, and industrial buildings use about one-third of all the energy consumed in the U.S. Although traditional energy-related research has primary encompassed design and control of equipment and systems, energy consumption can also be reduced through improved maintenance and servicing. Research in this area includes the development of computer automated techniques for condition monitoring, fault detection, and diagnostics. Reducing electric utility power demand through the use of new systems (e.g., thermal storage) and controls is also an important research area.

In recent years concerns with the *ozone depletion* and *global warming* problems have become additional focal points of the HVAC&R research programs. Prior to their phase-out, approximately one-third of the chlorofluorocarbons (CFCs) consumed in the U.S. were used in refrigeration and air-conditioning. CFCs are considered a major factor in ozone depletion and global warming problems. The changeover from CFCs to alternative refrigerants has had a major impact on equipment design and may also affect energy use. The next major environmental issue will probably be global warming. Many of the current refrigerants have a high direct global warming potential. In addition, global warming is strongly influenced by the energy efficiency of HVAC&R products, because the burning of fossil fuels generates CO_2, a major greenhouse gas.



The use of HVAC systems does not necessarily create a healthy indoor environment. Indeed, reports of symptoms and other health complaints related to indoor environments have been increasing. However, the majority of health problems reported in buildings (namely, nonspecific complaints sometimes called the sick building syndrome) cannot be attributed to specific exposures. Available evidence suggests that multiple factors are involved, including indoor air quality; physical conditions such as temperature, humidity, lighting, and noise; and social and/or psychological stressors. Poor indoor environment conditions cost around $20 to $160 billion in lost wages and productivity, administrative expenses, and health care in the U.S. Our research has thus focused on sustainable and environmentally-friendly building designs with more energy-efficient technologies for improving indoor environment, comfort, health, and safety. The technologies developed, such as natural ventilation and displacement ventilation systems, can substantially reduce greenhouse gas emissions and save money. Reduction in energy use and pollutant emission by those technologies can benefit global sustainability and energy conservation. Therefore, those technologies are contributing to the solution of the indoor environment and global pollution problems.

Furthermore, the terrorist attacks on New York City and Washington D.C. on September 11, 2001 and the following anthrax dispersion by mail have spawned concerns about various possible forms of terrorism, including airborne/aerosolized chemical and biological warfare agent (CBWA) attacks. Current enclosed environments, such as buildings and airliner cabins, are vulnerable, since they are not designed for such an attack. How to design a safe and secure enclosed environment that can protect occupants from such an attack is an urgent issue for the designers. Our effort in recent years has been at the development of fast and accurate models that can numerically simulate those attack scenarios and provide control strategies to protect occupants from such an attack.

In order to address both industry and societal concerns within the area of HVAC&R, fundamental engineering approaches to design and control of equipment and systems are needed. HVAC&R research is aimed at removing the scientific barriers to good designs, good control, development of suitable standards, and the utilization of proper materials. The HVAC&R area is an interdisciplinary research effort which includes a wide variety of projects in disciplines such as acoustics, vibrations, controls, mechanics, design, materials, thermodynamics, heat transfer, fluid mechanics, and computer science. The common goal is fundamental and applied research that will assist the HVAC&R community in the continuing evolution of improved heating and cooling equipment and systems. Research activity in the HVAC&R area is closely allied to the concerns of industry and with the programs of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), the Air-Conditioning and Refrigeration Institute (ARI), the Association of Home Appliance Manufacturers (AHAM), the International Institute of Refrigeration (IIR) and the International Institute of Ammonia Refrigeration (IIAR). Most of this research is conducted at the Ray W. Herrick Laboratories, a graduate student research facility of the School of Mechanical Engineering.

All research projects have a strong educational component, and virtually all lead to theses for either a Master of Science or Ph.D. degree. Most research funding for the programs is provided by industry, reflecting an unusually close link with companies and industry associations

A general description of recent research activities in the thermal systems area follows.

HVAC&R Equipment and System Modeling and Analysis

Simulation models are essential in the design of equipment and controllers and can be useful in evaluating the performance of new or improved concepts. The thermal systems area faculty have been involved with development and application of a variety of equipment and systems' models including: steady-state and transient models of vapor compression cooling equipment, transient models of building heating and cooling requirements, and furnace models that incorporate combustion, heat transfer, and acoustics. In general, the models have been validated using laboratory data and have been used to evaluate system behavior and/or identify design/control improvements.

Alternative Refrigerants and Alternative Technologies

Concern over the environment has spawned the investigation of both alternative refrigerants for vapor compression systems and alternative refrigeration technologies that use environmentally friendly working fluids. Earlier this decade, alternative refrigerant work at the labs focussed on the evaluation of alternatives to R-12 and R-22, such as single or multi-component HFC's and hydrocarbons. More recently, the emphasis has been on performance optimization, reliability issues, lubrication, and noise issues related to the alternatives that have been chosen. Current research into alternative refrigeration technologies includes the investigation of the transcritical CO_2 cycle technology for automotive and packaged air conditioning applications, thermoacoustic coolers for small-scale air conditioning and refrigeration, and secondary-loop refrigeration systems for supermarkets.

HVAC&R System Control and Diagnostics

"Smart" buildings of the future will incorporate intelligent control strategies that minimize operating costs and automated diagnostic features that identify problems that can lead to loss of comfort or excessive energy charges. The thermal systems area at Herrick is involved in the development of these technologies. The goal of the recent controls' research has been to develop simple supervisory control strategies for systems that incorporate thermal storage (ice or building mass) for cooling. The opportunity is to shift energy usage in an optimal fashion to take advantage of lower utility rates that occur during off-peak usage hours. The diagnostics work has focussed on vapor compression equipment, with projects on rooftop air conditioners and centrifugal chillers. It is envisioned that diagnostic techniques would reside in equipment controllers and utilize low-cost measurements to continuously monitor performance in order to detect and diagnose faults. Methods have been developed that can detect and diagnose common faults before there is about a 5% reduction in cooling capacity and efficiency.

Compressors

Compressor research has been the heart and soul of the Herrick Labs since its inception. Recent and current research on compressors at Herrick has focused on reliability, performance, modeling, and noise control of positive displacement compressors, such as scroll, rotary and reciprocating compressors. This ongoing work has been sponsored by many industrial sponsors. A complete listing can be found in the Herrick Labs brochure on "Compressor Research". The work has included the development of a model to aid in the design of discharge mufflers for rolling piston compressors. In addition, detailed mathematical models of hermetic scroll compressors for R-22 and R-410A, an automotive scroll compressor for R-134a, a novel hermetic rotary compressor, a hermetic two-stage rotary compressor, and a novel reciprocating compressor with integrated capacity modulation have been developed to obtain performance predictions. These models are being used as tools that allow parametric studies of design parameters that lead to improved compressor performance. These models include the analysis of the losses associated with heat transfer, refrigerant leakage, and friction. They predict the mass flow rate, the work input, the average discharge temperature and the temperature, pressure, and total mass in each compression chamber as a function of the orbiting angle. The influence of parameters such as leakage gaps, compressor materials, compressor geometry, speed and some general design parameters (e.g., location of the suction and discharge ports) can be studied using the models. Based on a study of these parameters, design improvements are being implemented by the industrial sponsors.

Two-Phase Flow Modeling

Proper design of heat exchangers, expansion devices, and flow distribution devices within air conditioning and refrigeration equipment requires good theoretical models for two-phase flow phenomenon. However, the physical phenomenon is difficult to characterize without the use of empirical data. Current research at the Labs includes the development of simple one-dimensional models that utilize empirical correlations and the development of three-dimensional CFD models that utilize only physical characteristics.

Miniature-Scale Refrigeration Systems

Thermal management of electronic components is a critical concern in developing faster, more compact and reliable computers. It is estimated that the next generation of computer chips could dissipate up to 200 W of heat. Since this is a significant increase in heat load dissipation, computer manufacturers are interested in examining other thermal cooling technologies that could be used instead of the usual spot cooling methods, which use fans and fin structures to cool electronic chips. Current studies at the Herrick Labs focus on evaluating the performance and feasibility of meso- and micro-scale refrigeration systems for electronics cooling. This new research program includes a comprehensive theoretical analysis of miniature-scale refrigeration systems and components such as miniatures-scale diaphragm and rotary compressors, integrated heat spreader and mini-channel evaporators, and the design and fabrication of other innovative solutions to cool electronics with a cooling capacity of up to 200 W.

Simulations of Airflow and Contaminant Transport

Simulations of airflow and contaminant transport are an effective method for the investigation of thermal comfort and indoor air quality in built environment. Large eddy simulation (LES) and Detached Eddy Simulation (DES) are next-generation tools to predict airflow in and around buildings and in an aircraft cabin, because LES and DES are universal, has few or no adjustable model coefficients, and can provide more flow information. We have developed different LES dynamic subgrid models that are suitable for both indoor and outdoor airflows, and advance numerical algorithm to reduce computing costs. The LES and DES are being applied for airflow in and around buildings and in commercial airliner cabin environment. Recently, we have developed a Fast Fluid Dynamics (FFD) model that can be used to predict airflow and contaminant transport in a room with a speed faster than real time. In addition, we have simulated the trajectories of particulate contaminants in an enclosed environment, such as a room or an aircraft cabin. The study uses the Lagrangian model to trace the particle motion by a program with Reynolds averaged Navier-Stokes equations. Drag, buoyancy and Brownian forces are being considered in the motion equations. The modeling of momentum and energy exchange between air and particles is also established according to the theoretical analysis and experimental data.

Advanced Windows

Advanced building facade system can conserve energy and improve indoor air quality in buildings. Jointly with International Energy Agency Annex 44, an advanced window system has been developed for use in both commercial and residential buildings. The increased costs for producing such a window is minimal compared with a conventional high quality window, but the new window can have a heat recovery efficiency of 20-56% depending on the climate conditions. Most importantly, the new window can supply fresh air to a room to maintain good air quality.

Novel Air Distribution Systems for Commercial Airliner Cabins

Passengers and crew are packed in a very limited space in commercial aircraft cabins. The air distribution systems play a very important role for the comfort, health, and safety of passengers and crew. The recent experience of SARS transmission on aircrafts has further heightened the need to improve the design of the air distribution systems currently used on airplanes. Our study uses a validated CFD program to analyze thermal comfort and air quality by simulating passengers with reasonable detail for a twin-aisle cabin. Novel ventilation systems with high energy efficiency and good airborne infectious disease control, such as personalized ventilation and displacement ventilation, have been developed.

Faculty of the Thermal Systems Research Group

The following faculty members make up the Thermal Systems Research Group:

James E. Braun (Professor of Mechanical Engineering): Thermal systems modeling, analysis, design optimization, control optimization, and diagnostics with applications to space conditioning and refrigeration systems.

Qingyan Chen (Professor of Mechanical Engineering): Indoor and outdoor airflow modeling by computational fluid dynamics and measurements, protection of buildings from chemical/biological warfare agent attacks, building ventilation systems, indoor air quality, building energy analysis.

Eckhard A. Groll (Professor of Mechanical Engineering): Thermal sciences as applied to advanced HVAC&R systems and their working fluids: alternative refrigeration technologies, vapor compression systems using environmentally friendly refrigerants, such as HFCs and natural refrigerants, analysis and optimization of individual components of HVAC&R systems, such as compressors and heat exchangers.

The following faculty members are partly associated with the Thermal Systems Research Group,

Brandon E. Boor (Assistant professor of Civil Engineering). Indoor & urban air pollution, aerosol science, airborne nanoparticles, low-cost air quality monitoring, health effects of air pollution, ventilation & filtration strategies for low-energy buildings, air quality.

Suresh V. Garimella (Professor of Mechanical Engineering). High-performance cooling technologies, microelectronics packaging/cooling, microscale thermal phenomena, interface dynamics/tracking, electronic and composite materials processing.

W. Travis Horton (Associate Professor of Civil Engineering). Thermal sciences and energy conversion systems, including heating, air conditioning, refrigeration, and electrical systems; combined heat and power systems, and building energy modeling techniques.

Galen B. King (Professor of Mechanical Engineering). Optics, optical and laser-based measurements, engineering instrumentation, biomedical instrumentation.

Panagiota Karava (Associate Professor of Civil Engineering). Natural/hybrid ventilation, building airflows, building-integrated photovoltaic-thermal systems, building energy modeling and simulation, design and analysis of energy efficient buildings, indoor environment, sustainable building construction, wind effects on buildings and their environment

Ming Qu (Associate Professor of Civil Engineering). Integrated design, construction and operation of buildings, engineering aspects related to the built environment-structures, mechanical systems (HVAC), electrical/lighting systems, building envelope, indoor environment

Thanos Tzempelikos (Associate Professor of Civil Engineering). Design of energy-efficient buildings, advanced building envelopes, indoor environment, dynamic facades, daylighting, glazings, shading design and control, lighting controls, integration of green and renewable technologies, solar energy applications, photovoltaics, building energy modeling and simulation.

Thermal Systems Research Facilities

Experimental facilities, instrumentation, and equipment for data acquisition, reduction, computation, and display are available for testing HVAC&R components and systems. Some of the more significant facilities are described below.

Psychrometric Chambers

The laboratory has two 7000 ft^3 (200 m^3) psychrometric rooms that can simulate indoor and outdoor conditions and be used to study the performance of heating and cooling equipment. The rooms were specifically designed to accommodate ASHRAE/ARI standard test procedures used in rating unitary air-conditioners and heat pumps up to a capacity of 5 tons of refrigeration (18 kW). In addition they have been used for many different experiments where operation under specified temperature and humidity is required. The rooms were designed to simulate either outdoor conditions having a dry bulb temperature range from -10 to 130^{o}F (-23 to 55^{o}C) or indoor conditions having a dry bulb temperature range of -10 to 90^{o}F (-23 to 32^{o}C). In addition, the relative humidity can be varied over a wide range of conditions at any temperature.

Both rooms can maintain both the wet and dry bulb temperatures to within 1% over the entire temperature and humidity range. They are capable of holding these tolerances for both transient and steady state running condition. The control of the rooms is fully automated and they can be programmed to run a series of steady-state tests or to simulate transient load conditions that occur in buildings.

Indoor Environment Chambers

A newly built full-scale environmental chamber facility of 8 m x 5.6 m x 2.7 m is available for studying thermal comfort, indoor air quality, and energy consumption of HVAC systems. The $500K facility consists of two chambers: a test chamber that simulates an indoor space and a climate chamber that simulates an outdoor space from very cold to very warm and humid conditions. Each chamber has a separate HVAC system that controls the chambers to the desired thermal and flow conditions. The facility has two separated HVAC systems and a high precision control system. The facility has 70 hot sphere anemometers; one tracer-gas system for simulating different contaminants, including chemical/biological agents in gaseous form; two particle counters; one particle dozer for simulating particulate contaminants; one flow visualization system; and one temperature measuring system.

Psychrometric Wind Tunnel

The laboratory is equipped with an environmentally controlled wind tunnel test facility that can be used to evaluate air-side heat transfer coefficients and pressure drops, as well as the frosting behavior of new or substitute refrigerants for many different heat exchanger and coil designs. The wind tunnel test facility can also be used to simulate indoor or outdoor conditions in combination with the psychrometric test chambers for testing split systems, such as residential heat pumps and air-conditioners or commercial refrigeration systems.

Large Equipment Laboratory

A large portion of the Herrick Laboratories is dedicated to investigating the performance, efficiency, noise, and vibration of large HVAC&R equipment with cooling capacities of up to 100 tons. A large test setup was recently constructed for testing diagnostic methods applied to a 90-ton centrifugal chiller. In addition, a fully operational ice storage system is setup in this part of the laboratory. The system can be used to evaluate the performance of alternative control methods or cooling coils under a variety of time-varying conditions.

Thermo-Mechanical Testing Facilities

The 9hermos-mechanical testing facilities include a high temperature furnace (up to 3100^{o}F (1700^{o}C)) with a programmable microprocessor controller that can be used to perform automatic thermal cyclic tests. The environment of the furnace can be controlled by introducing inert gases in order to prevent oxidation effects. This set-up can be used to perform a combination of controlled thermal and mechanical cyclic loads. In addition, an infra-red heating apparatus is available to study the effects of localized heating on 9hermos-mechanical fracture and fatigue behavior.

Compressor Testing

A fully automated hot-gas bypass load stand is available for testing HFC compressors with cooling capacities between 1 and 3 tons. Operating conditions are controlled using electronic expansion valves that modulate the flow of refrigerant through and bypassing a condenser. The controls are fully automated so that load stand can generate conditions necessary to develop a compressor map at a range of inlet and outlet pressures and inlet superheat. In addition, a hand operated hot-gas bypass load stand is available for performance testing of carbon dioxide compressors with cooling capacities from 1 to 3 tons. Furthermore, a hand operated hot-gas bypass load stand is available for performance testing of miniature-scale compressors for electronics cooling with cooling capacities of up to 400 W. Finally, a fully instrumented compressor calorimeter is available for testing HFC compressors with cooling capacities of up to 5 tons.

High Pressure, Tube-In-Tube Heat Transfer Test Facility

The high-pressure, tube-in-tube heat transfer test facility is optimized to create realistic flow conditions and to permit accurate measurement of in-tube heat transfer and pressure drop with alternative refrigerants during two-phase condensation and evaporation, and also during single-phase cooling and heating processes.

Bench Testing

Over 4500 ft^2 (420 m^2) of laboratory space is available for bench testing. This space is equipped with electric power, low and high pressure steam, hot and cold water, natural gas, drains, and ventilation systems. This space provides an excellent area to set up small bench tests. In the past, bench testing rigs have been designed for studying: 1) small-scale bread-board systems, such as thermoacoustic coolers, 2) refrigerant flow and energy losses through various valves, 3) flow and heat transfer through capillary tubes and expansion valves, and 4) heat exchangers that are exposed to open flames, such as furnaces, swimming pool heaters, and commercial food cookers.

Theses

Following is a listing from the last 15 years of theses in the Thermal System Research Area. For a comprehensive listing of all theses, please contact the Laboratories.

Name	Degree	Professor		Thesis Title*
Wahlberg, C.J.	MSME 8/95	Goldschmidt, V.W.		A Compressor Performance Evaluation of Hydrocarbon Refrigerants
Rossi, T.M, HL 95-13	Ph.D. 12/95	Braun, J.E.		Detection, Diagnosis, and Evaluation of Faults in Vapor Compression Cycle Equipment
Kim, Y.K. HL 95-20P	MSME 12/95	Soedel, W.		The Analysis and Simulation of Gas Pulsations in a Valve-Muffler System of a Rolling Piston Compressor
Douglas, J.D. HL 95-21	MSME 12/95	Braun, J.E.		A Cost-Based Method for Comparing Alternative Refrigerants Applied to R-22 Systems
Navarro de Andrade, J.E.	MSME 12/95	Goldschmidt, V.W.		Investigation of Rotary Compressor Oil Carry-Over
Minner, B.L. HL 96-6	MSME 8/96	Braun, J.E.		Design Optimization for Thermoacoustic Cooling Systems
Temple, K.A. HL 96-7	Ph.D. 8/96	Goldschmidt, V.W.		Thermal and Internal Acoustic Model of a Helmholtz Type Pulse Combustion Furnace
Aldrin, J.C. HL 96-2P	MSME 5/96	Soedel, W.		Investigation of Vibration Control Systems Applied to Automatic Washer Suspension Design
Lai, P. C.-C. HL 96-8P	Ph.D. 12/96	Soedel, W.		General Procedure for the Analysis of Gas Pulsations in Thin Compressor or Engine Manifolds and Thin Shell Type Mufflers
Davis, C.	MSME 5/97	Braun, J.E.	N/T	Evaluation of Steady-State Detectors for Fault Detection and Diagnostics
LeRoy, J. HL 97-25	MSME 9/97	Groll, E.A./ Braun, J.E.		Capacity and Power Demand of Unitary Air Conditioners and Heat Pumps Under Extreme Temperature and Humidity Conditions
West, J.D. HL 97-23	MSE 9/97	Braun, J.E.		Evaluation of Methods For Controlling Ice Storage Systems

Breuker, M. HL 97-29	MSME 12/97	Braun, J.E.		Evaluation of a Statistical, Rule-Based Fault Detection and Diagnostics Method for Vapor Compression Air Conditioners
Harris, D. HL 97-19	Ph.D. 12/97	Goldschmidt, V.W.		Heat Transfer Processes of Serpentine Tubular Heat Exchangers
Halm, N.P. HL 97-31P	MSME 12/97	Groll, E.A./ Braun, J.E./ Tree, D.R.		Mathematical Modeling of Scroll Compressors
Hommema, S.E. HL 97-33	MSME 12/97	Goldschmidt, V.W.		Condensation Heat Transfer in Pulsating Flow
Song, H.J.	MSME 12/97	Soedel, W.		Investigation of Liquid Hammer By Modal Analysis
Causey, A.E. HL 98-12	MSME 4/98	Braun, J.E./ Groll, E.A.	N/T	Compressor Load Stand: Commissioning and Control Strategies
Montgomery, K.W. HL 98-17	MSME 9/98	Braun, J.E.		Development of Analysis Tools for the Evaluation of Thermal Mass Control Strategies
Skowron, E.B. HL 98-20P	MSME 12/98	Goldschmidt, V.W./ Groll E.A.		Investigation of Refrigerant/Oil Flow through Suction Accumulators
Comstock, M. HL 99-20	MSME 12/99	Braun, J.		Development of Analysis Tools for the Evaluation of Fault Detection and Diagnostics in Chillers
Marcus, B.F. HL 99-25P	MSME 12/99	Groll, E.A./ Goldschmidt, V.W.		Effects of Applications on Reliability of Performance of Unitary Split Systems
Pitla, S.S. HL 99-10	MSME 8/99	Groll, E.A./ Ramadhyani, S.		Heat Transfer Characteristics of Supercritical CO_2
Blake, L. HL 2000-1P	MSE 5/00	Franchek, M./ Goldschmidt, V.W.		Micron-Sized Particle Adhesion on Surfaces and Effects of Oil Presence on Adhesion
Chaturvedi, N. HL 2000-15	MSME 12/00	Braun, J.E.		Analytical Tools for Dynamic Building Control
Chen, B. HL 2000-16	MSME 12/00	Braun, J.E.		Evaluating the Potential of On-Line Fault Detection and Diagnostics for Rooftop Air Conditioners
Chen, Y. HL 2000-17P	Ph.D. 12/00	Groll, E.A.		Mathematical Modeling of Scroll Compressors

Fang, L. HL 2000-8P	Ph.D. 8/00	Goldschmidt, V.G./ Abraham, J.		A Computational and Experimental Investigation of Clamshell Heat Exchangers in Residential Gas Furnaces
Maulik, I.	MSME 8/00	Mongeau, L./ Braun, J.	N/T	Effects of Body Forces on Thermodynamic Cycles
Robinson, D.M.	Ph.D. 5/00	Groll, E.A.		Modeling of Carbon Dioxide Based Air-to-Air Air Conditioners
Alexander, A. HL 2001-18	MSME 8/01	L. Mongeau/ J. Braun	N/T	Performance of Straight-Fin and Microchannel Heat Exchangers in Steady and Periodic Flows
Li, D. HL 2001-7	MSME 5/01	Groll, E.A.		Theoretical and Experimental Investigation of a Carbon Dioxide Based Air Conditioning System
Li, G. HL 2001-19P	MSME 8/01	Braun, J.E./ Groll, E.A./ Frankel, S.H.		A Numerical and Experimental Investigation of Refrigerant Flow Control Devices
Shinde, N.	MSME 8/01	Chiu, G.		Feasibility Study for the Design and Fabrication of a Mesoscale Pulse Tube Refrigerator
Sun, Z. HL 2001-8	MSME 5/01	Groll, E.A.		CO_2 Flow Boiling Heat Transfer in Horizontal Tubes
Baek, J.S. HL 2002-10	Ph.D. 8/02	Groll, E.A./ Lawless, P.B		Development of a Carbon Dioxide Based Field Deployable Environmental Control Units to Replace FC-22 or HFC-134a Units
Harms, T.M. HL 2002-13	Ph.D. 8/02	Groll, E.A./ Braun, J.E.		Charge Inventory System Modeling Validation on Unitary Air Conditioners
Horton, W.T. HL 2002-3	Ph.D. 5/02	Groll, E.A.		Modeling of Secondary Loop Refrigeration Systems in Supermarket Applications
Jovane, M.	MSME 8/02	Braun, J.E./ Groll, E.A.	+N/T	Phase Separator Optimization
Kim, J.H. HL 2002-14	MSME 8/02	Groll, E.A./ Braun, J.E.		Performance Comparison of a Unitary Split System Using Microchannel and Fin-Tube Outdoor Coils
Ortiz, T. HL 2002-17	Ph.D. 8/02	Groll, E.A.		Development of a New Model for Investigation of the Performance of Carbon Dioxide as a Refrigerant for Residential Air Conditioners

Trutassanawin, S.	MSME 12/02	Groll, E.A.	N/T	Testing of Transcritical CO_2 Breadboard Air Conditioning Systems
Mercer, K. HL 2003-3	MSME 5/03	Braun, J.E.		Modeling and Testing Strategies for Evaluating Ventilation Load Reduction Technologies
Hubacher, B. HL 2003-24	MSME 12/03	Groll, E.A.		Experimental and Theoretical Performance Analysis of Carbon Dioxide Compressors
Lawrence, T. HL 2004-2	Ph.D. 5/04	Braun, J.E.		Methodologies for Evaluating Demand-controlled Ventilation Retrofits in HVAC Applications.
Bendapudi, S. HL 2004-12	Ph.D. 8/04	Braun, J.E.		Development and Evaluation of Modeling Approaches for Transients in Centrifugal Chillers
Yang, Li HL 2004-13	MSME 8/04	Braun, J.E./ Groll, E.A.		The Impact of Fouling on the Performance of Filter-Evaporator Combinations and Rooftop Air Conditioners
Li, Haorong HL 2004-14	Ph.D. 8/04	Braun, J.E.		A Decoupling-Based Unified Fault Detection and Diagnosis Approach for Packaged Air Conditioners
Zhang, Zhao	MSME 5/05	Chen, Y.		A Study on Transport and Distribution of Indoor Particulate Matter
Lau, Josephine	MSME 8/05	Chen, Y.		The Performance of Floor-Supply Displacement Ventilation in Workshop Configurations with Measurements and Simulation Studies
Chervil, Rudy	MSME 8/05	Heber A., Braun J.E./Groll, E.A.		Air Pollutant Emissions and Mitigation by Diet Manipulation at Two High-Rise Layer Barns
Zhou, Xiaotang (HL 2005-12)	Ph.D. 12/05	Braun, J.E.		Dynamic Modeling of Chilled Water Cooling Coils
Bertsch, Stefan (HL 2005-13P)	MSME 12/05	Groll, E.A.		Theoretical and Experimental Investigation of a Two Stage Heat Pump Cycle for Nordic Climates
Kim, Jun-Hyeung (HL 2005-14)	Ph.D. 12/05	Groll, E.A.		Analysis of a Bowtie Compressor with Novel Capacity Modulation
Shen, Bo (HL 2006-1)	Ph.D. 5/06	Groll, E.A./Braun, J.E.		Improvement and Validation of Unitary Air Conditioner and Heat Pump Simulation Models at Off-Design Conditions

Li, Daqing (HL 2006-4)	Ph.D. 5/06	Groll, E.A.		Investigation of an Ejector-Expansion Device in a Transcritical Carbon Dioxide Cycle for Military ECU Applications
Hugenroth, Jason J. (HL 2006-8P)	Ph.D. 5/06	Braun, J./Groll, E./King, G.		Liquid Flooded Ericsson Cycle Cooler
Trutassanawin, S.	Ph.D. 8/06	Groll, E.A./ Garimella, S.		A Miniature-Scale Refrigeration System for Electronics Cooling
Gosselin, Jennifer	MSME 8/06	Chen, Y.		A Ventilated Window for Indoor Air Quality Improvement in Residential Buildings
Lee, Kyoung Ho (HL 2006-18)	Ph.D. 12/06	Braun, J.E.		Demand-Limiting Control Using Building Thermal Mass in Commercial Buildings
Wang, Liangzhu	Ph.D. 5/07	Chen, Y.		Coupling of Multizone and CFD Programs for Building Airflow Distribution and Contaminant Transport Simulations
Zhang, Tengfei	Ph.D. 5/07	Chen, Y.		Detection and Mitigation of Contaminant Transport in Commercial Aircraft Cabins
Chen, Xi	MSME 8/07	Chen, Y.		A Numerical Study on Decontaminating Unoccupied Airliner Cabins
Jované, Miguel (HL 2007-7)	Ph.D. 8/07	Braun, J./Groll, E.		Modeling and Analysis of a Novel Rotary Compressor
Wichman, Adam (HL 2007-8)	MSME 8/07	Braun, J.		Evaluation of Fault Detection and Diagnosis Methods for Refrigeration Equipment and Air-Side Economizers
Wright, Anthony (Tony)	MSME 2007	Groll, E.	N/T	(Non-thesis) Rapid-fire Combustion Engine
Zhang, Zhao	Ph.D. 12/07	Chen, Y.		Modeling of Airflow and Contaminant Transport in Enclosed Environments
Sathe, Abhijit	Ph.D. 8/08	Groll, E.		Miniature-Scale Diaphragm Compressor for Electronics Cooling
Zhong, Zhipeng (HL 2008-3)	Ph.D. 8/08	Braun, J.		Combined Heat and Moisture Transport Modeling for Residential Buildings
Bertsch, Stefan	Ph.D. 8/08	Groll, E.		Refrigerant Flow Boiling in Microchannel Evaporators
Kim, Woohyun (HL 2009-12)	MSME 12/09	Braun, J.		Evaluation of a Virtual Refrigerant Charge Sensor

Mazumdar, Sagnik	Ph.D. 12/09	Chen, Y.		Transmission of Airborne Contaminants in Airliner Cabins
Zuo, Wangda	Ph.D. 5/10	Chen, Y.		Advanced Simulations of Air Distributions in Buildings
Hengeveld, Derek (HL 2010-9)	Ph.D. 12/10	Braun, J./Groll, E.		Development of a System Design Methodology for Robust Thermal Control Subsystems to Support Responsive Space
Gupta, Jitendra	Ph.D. 12/10	Chen, Y.		Respiratory Exhalation/Inhalation Models and Prediction of Airborne Infection Risk in an Aircraft Cabin
Bell, Ian (HL 2011-4)	Ph.D. 5/11	Braun, J./Groll, E.		Theoretical and Experimental Analysis of Liquid Flooded Compression in Scroll Compressors
Leffler, Robert	MSME 5/11	Groll, E.		Power Plant Waste Heat Rejection and Utilization Options
Wang, Miao	Ph.D. 5/11	Chen, Y.		Modeling Airflow and Contaminant Transport in Enclosed Environments with Advanced Models
Mathison, Margaret (HL 2011-5)	Ph.D. 8/11	Braun, J./Groll, E.		Modeling and Evaluation of Advanced Compression Techniques for Vapor Compression Equipment
Vargo, Matt	MSME 5/11	Braun, J.	N/T	Compressor Performance Testing
Rao, Sagar	MSME 2011	Tzempelikos, Thanos		Thermal and Daylighting Analysis of Building Perimeter Zones
Rohan, Devin	MSME 2011	Tzempelikos, Thanos		A Dynamic Advanced Radiation Exchange Module for Use in Simulation of Spaces with Radiant Systems
Bilal, Nasir	Ph.D. 8/11	Adams, D.		Design Optimization of the Suction Manifold of a Reciprocating Compressor Using Uncertainty and Sensitivity Analysis
Lee, Ki Sup	Ph.D. 12/11	Chen, Y.		Air Distribution Effectiveness and Thermal Stratification with Stratified Air Distribution Systems
Xue, Guangqing	MSME 12/11	Chen, Y.		Design Tool for Under-Floor Air Distribution System

Shaffer, Bryce	Ph.D. 5/12	Groll, E.		Performance Analysis of Non-Metallic Dry Running Scroll Compressors
Faussett, Tom	MSME 5/12	Groll, E.	N/T	Optimizing Refrigerant Distribution in a Evaporator of a Large Room Cooling System
Kincaid, Nicholas	MSME 5/12	Groll, E.	N/T	Humidity Ratio Detection as a Means of Dryer Cycle Termination
Inamdar, Harshad	MSME 5/12	Groll, E.	N/T	Performance Comparison of Two-Phase Fluids in Heat Pipes for Electronics Cooling
Bradshaw, Craig	Ph.D. 8/12	Groll, E.		A Miniature-Scale Linear Compressor for Electronics Cooling
Krishna, Abhinav	MSME 8/12	Groll, E.		Organic Rankine Cycle with Solution Circuit for Low-Grade Heat Recovery
Ramaraj, Sugirdhalakshmi	MSME 12/12	Groll, E.		Vapor Compression Cycle Enhancements for Cold Climate Heat Pumps
Ruhno, Amanda	MSME 5/13	Groll, E.	N/T	Minerva Built in Cavity Heat Distribution Analysis Model
Nyika, Simbarashe	MSME 5/13	Braun, J.		Development, Validation and Application of General Gray-Box Models for Ductless and Ducted Residential Heat Pumps
Pathak, Anchalika	MSME 5/13	Groll, E.	N/T	Design and Construction of an Organic Rankine Cycle Test Stand
Spicer, Tom	MSME 5/13	Groll, E.	N/T	Centripetal Moisture Extraction in a Vertical Axis Washing Machine
Kultgen, Derek	MSME 5/13	Hutsel, W./Groll, E./Motevalli, V.		Assessing the Energy Reduction Potential of a Cold Climate Heat Pump
Holloway, Seth	MSME 5/13	Horton, W.T.		An Annual Performance Comparison of Various Heat Pumps in Residential Applications
Song, Yuanpei	MSME 5/13	Braun, J./Groll, E.		Modeling and Experimental Validation of a Multi-Port Vapor Injected Scroll Compressor
Ebling, Steffen	MSME 8/13	Groll, E.		Carbon Dioxide Compressor Load Stand
Kim, Woo Hyun	Ph.D. 12/13	Braun, J.		Fault Detection and Diagnosis for Air Conditioners and Heat Pumps Based on Virtual Sensors

Flueckiger, Scott	Ph.D. 12/13	Groll, E.		Multiscale Simulation of Thermocline Energy Storage for Concentrating Solar Power
Xue, Yan	MSME 12/13	Chen, Y.		Determination of Heat Transfer in Under-Floor Plenums in Buildings with Under-Floor Air Distribution Systems
Caskey, Stephen	MSME 12/13	Groll, E.		Cold Climate Field Test Analysis of an Air-Source Heat Pump with Two-Stage Compression and Economizing
Rai, Aakash	Ph.D. 5/14	Chen, Y.		Ozone-Initiated Chemistry in Indoor Environment
Liu, Wei	MSME 5/14	Chen, Y.		Experimental and Numerical Study of the Air Distribution in an Airline Cabin
Bach, Christian	Ph.D. 5/14	Groll, E./Braun, J./Horton, T.		Refrigerant Side Compensation of Air-Side Maldistribution of Evaporators and Its Effects on System Performance
Jin, Mingang	Ph.D. 5/14	Chen, Y.		Building Airflow Simulations with Fast Fluid Dynamics
Quock, Matthew	MSME 5/14	Groll, E.	N/T	Heat Exchanger Performance Optimization
Stuart, Nicholas (Nico)	MSME 5/14	Groll, E.	N/T	Heat Exchanger Performance Optimization
Cheung, Howard HL 2014-4	Ph.D. 8/14	Braun, J.		Inverse Modeling of Vapor Compression Equipment to Enable Simulation of Fault Impacts
Upathumchard, Ularee HL 2014-6	MSME 12/14	Groll, E.		Waste Heat Recovery Options in a Large Gas-Turbine Combined Power Plant
Yuill, David HL 2014-8	Ph.D. 12/14	Braun, J.		Development of Methodologies for Evaluating Performance of Fault Detection and Diagnostics Protocols Applied to Unitary Air-Conditioning Equipment
Bansal, Kunal	MSME 8/15	Braun, J.		Modeling and Evaluation of Scroll Expanders for a Liquid-Flooded Ericsson Power Cycle
Dharkar, Supriya	MSME 8/15	Groll, E.		CO2 Heat Pumps in Commercial Building Applications with Simultaneous Heating and Cooling Demand

Kim, Donghun HL 2015-7	Ph.D. 8/15	Braun, J.		Development and Applications of Models and Algorithms for Model-Predictive Control in Buildings
Krishna, Abhinav HL 2015-9	Ph.D. 12/15	Groll, E.		Analysis or a Rotating Spool Expander for Organic Rankine
Kung, Yi-Shu	Ph.D. 5/15	Qu, Ming		An Integrated System of Vapor-Compression Chiller and Absorption Heat Pump: Experiment, Modeling and Energy, and Economic Evaluation
Reddy, Lalitya	MSME 5/15	Tzempelikos, T.	N/T	Visual Comfort Studies in Open Plan Offices
Schneemann, Jason	MSME 5/15	Groll, E.	N/T	Sustainable Water Systems at the ReNEWW (Retrofitted Net-Zero Energy, Water and Waste) House
Shi, Zhu	MSME 5/15	Chen, Y. and Chen, J.		Numerical Simulation and Characterization of Jet Flows in Indoor Environments
Vasudevan, Jebaraj HL 2015-6	MSME 12/15	Horton, W.T.		Training and Evaluation of Virtual Sensors for Rooftop Units
Wang, Haojie	MSME 5/15	Chen, Y.		Modeling on Single-Sided Wind Driven Natural Ventilation
Hung, Yu-Wei	MSME 8/15	Horton, W.T.	N-T	Development of Research Facilities for Chilled Beam Testing
Wani, Chaitanya	MSME 8/15	Groll, E.	N/T	Organic Rankine Cycle Using Scroll Expander
Woodland, Brandon HL 2015-5	Ph.D. 8/15	Braun, J.		Methods of Increasing Net Work Output of Organic Rankine Cycles for Low-Grade Waste Heat Recovery with a Detailed Analysis Using a Zeotropic Working Fluid Mixture and Scroll Expander
Wang, Xiaoshen	MSME 12/15	Groll, E.	N/T	Performance Evaluation of Different Valve Control Strategies for Building HVAC Systems
Whitman, Joshua	MSME 5/15	Groll, E.	N/T	Design of a Small Scale Cooling System for Application in Countertop Kitchen Appliances

Accorsi, Felipe HL 2016-2	MSME 5/16	Groll, E.		Experimental Characterization of Scroll Expander for Small-Scale Power Generation in an Organic Rankine Cycle
Bae, Yeonjin HL 2016-3	Ph.D. 8/16	Horton, W.T.		Integrated Design Tool of Building System Optimization for Building Life Cycle Cost
Chan, Ying-Chieh	Ph.D. 8/16	Tzempelikos, T.		Integrated Analysis of Building Perimeter Zones with Multi-Functional Façade Systems
Cheng, Li	MSME 8/16	Horton, W.T.	N/T	Assessment of Alternative Technologies for Sustainable Housing Developments
Czapla, Nicholas	MSME 8/16	Groll, E.		Performance Testing of a Unitary Split-System Heat Pump Utilizing an Energy Recovery Expansion Device
Graban Allison	MSME 5/16	Groll, E.	N/T	Heat Pump Dryer
Graham, Todd	MSME 5/16	Groll, E.	N/T	TIRA – Thermally Integrated Residential Appliances
Lumpkin, Domenique	MSME 5/16	Groll, E.	N/T	Performance of an Air Cycle Heat Pump
Venkatachalam, Sanjeev	MSME 8/16	Horton W.T.	N/T	Modeling of Desiccant Wheel-Based Cooling System
Jeon, Bonggil HL 2016-5	Ph.D. 12/16	Horton, W.T.		A Method for Selecting HVAC Retrofit Solutions for Existing Small- and Medium-Sized Commercial Buildings
Keivan Esfahani, Darioush	MSME 12/16	Li, K.M.	N/T	Gear Vibration Analysis
Kesto, Nathan	MSME 5/16	Groll, E.	N/T	Dryer End-of-Cycle Detection
Kim, Janghyun	Ph.D. 12/16	Horton, W.T.		Evaluating the Performance of Chilled Beams with Respect to Energy Efficiency and Thermal Comfort
Konstantzos,Iason	Ph.D. 12/16	Tzempelikos, T.		A Human-Centered Approach for the Design of Perimeter Office Spaces Based on Visual Environment Criteria

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