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 CO₂, 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 focused 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 CO₂ 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 focused 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,

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 (Assistant Professor 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 (Assistant 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 (Assistant 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 (Assistant 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°F (-23 to 55°C) or indoor conditions having a dry bulb temperature range of -10 to 90°F (-23 to 32°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 conditions. 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 thermo-mechanical testing facilities include a high temperature furnace (up to 3100°F (1700°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 thermo-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 ft² (420 m²) 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.

<table>
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<th>Name</th>
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<th>Professor</th>
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<td>Wahlberg, C.J.</td>
<td>MSME</td>
<td>Goldschmidt, V.W.</td>
<td>A Compressor Performance Evaluation of Hydrocarbon Refrigerants</td>
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<td>Rossi, T.M., HL 95-13</td>
<td>Ph.D.</td>
<td>Braun, J.E.</td>
<td>Detection, Diagnosis, and Evaluation of Faults in Vapor Compression Cycle Equipment</td>
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<td>Navarro de Andrade, J.E., HL 95-2P</td>
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<td>Minner, B.L., HL 96-6</td>
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<td>Temple, K.A., HL 96-7</td>
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<td>Thermal and Internal Acoustic Model of a Helmholtz Type Pulse Combustion Furnace</td>
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<td>Aldrin, J.C., HL 96-2P</td>
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<td>Lai, P. C.-C., HL 96-8P</td>
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<td>General Procedure for the Analysis of Gas Pulsations in Thin Compressor or Engine Manifolds and Thin Shell Type Mufflers</td>
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<td>Davis, C.</td>
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<td>West, J.D., HL 97-23</td>
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<td>Breuker, M.</td>
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Mercer, K.
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MSME
Braun, J.E.
Modeling and Testing Strategies for Evaluating Ventilation Load Reduction Technologies

Hubacher, B.
HL 2003-24
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Groll, E.A.
Experimental and Theoretical Performance Analysis of Carbon Dioxide Compressors

Lawrence, T.
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Braun, J.E.
Methodologies for Evaluating Demand-controlled Ventilation Retrofits in HVAC Applications.

Bendapudi, S.
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Yang, Li
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The Impact of Fouling on the Performance of Filter-Evaporator Combinations and Rooftop Air Conditioners

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Shen, Bo
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Improvement and Validation of Unitary Air Conditioner and Heat Pump Simulation Models at Off-Design Conditions

Li, Daqing
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<td>Hugenroth, Jason J.</td>
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