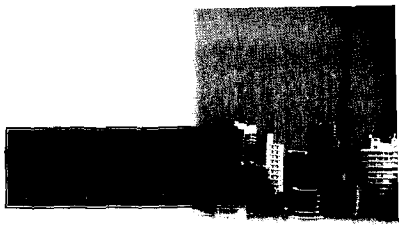

CO_2 Transcritical Cycle Research at CEEE

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1991년에 Maryland 대학에 Dr. Reinhard Rader-macher에 의해 환경에너지공학연구소(CEEE)가 설립되었다. 이 연구소는 환경 및 경제적인 관점에서 에너지 변환 시스템을 개발하는데 선두적인 역할을 수행해왔다. 환경 에너지 공학 연구소는 산업체, 정부, 및 연구소에서 지원 받는 컨소시엄 형태의 연구 센터이다. 대체 냉매, CO_2 초월임계 사이클에 관한 연구를 1993년에 시작한 이래, 현재 세계적으로 40여 개의 회사가 지원을 하고 있다. 2단 압축 CO_2 사이클 최적화, 초월 임계 사이클에서의 오일에 따른 열전달 영향, 초월 CO_2 임계 시스템에서의 오일 정체, CO_2 압축기 모델링, 자동차에서의 CO_2 기후 조절 시스템, CO_2 냉매를 이용한 에어컨, CO_2 저온 냉동 시스템 등에 관한 연구를 수행하고 있다.

CEEE는 향후 연구로 구성요소 및 시스템 최적화, 효율향상, 시스템 적용확대에 관한 연구를 할 예정이다. 센터는 보고서, 컨소시엄 미팅, 워크샵, 교과목 개설, 방문 연구자 초청 등을 통해 산업계 및 기술을 전달하고 있다.

본 고에서는 환경에너지 공학 연구소에서 CO_2 초월임계 사이클에 초점을 맞추어 연구소의 연구활동을 기술 한다.

The director of the Center for Environmental Energy Engineering (CEEE), Dr. Reinhard Radermacher, co-founded the Center at the University of Maryland in 1991. The Center is taking the lead in developing energy conversion systems that meet environmental and economic concerns. Research at CEEE is organized in consortia that are sponsored by industry, government and research institutions. Research on refrigerant alternatives, especially for the CO_2 transcritical cycle, was initiated at CEEE in 1993. The research in the Center is now supported by more than 40 companies worldwide. This article summarizes research activities of CEEE focusing on the CO_2 transcritical cycle research.

Vision and Mission of CEEE

The vision of the Center is "To be an international leader in research and education in environmentally responsible and economically feasible distributed energy conversion systems for buildings and transportation." The Center provides innovative solutions to the industry's research and development challenges and cost-effective, timely technology transfer. The mission of the Center is as follows:

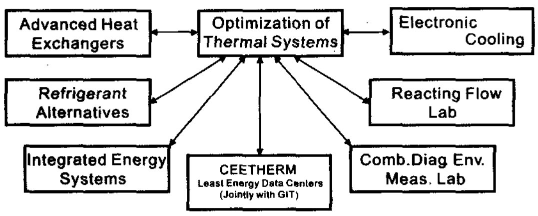
- To provide tools and information to support sponsors' strategic technology decisions
- To develop productive solutions to the industry's research and development challenges through
  - R & D of new components and systems
  - User-friendly, verified, task oriented simulation tools
- To provide excellent, cost effective, timely results and technology transfer
- To educate a new generation of creative, team-oriented engineering professionals, the future leaders in their fields..

Research Consortia of CEEE

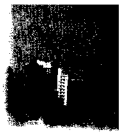
The Center has developed a highly flexible and task-oriented consortium structure that emphasizes pre-competitive research. Sponsors include industrial companies and government agencies that pool research funds leveraged by significant, additional support from the University of Maryland. Consortium projects assist sponsors in developing tomorrow's products through our mission.

Figure 1 shows the current structure of the Center's consortia and laboratories. Projects are carefully designed to ensure that research results enable sponsors to strengthen their competitive positions. In brief, the overview of each consortium is as follows:

- **Advanced Heat Exchangers Consortium**: identifies emerging technologies in heat exchanger design and enhancement and evaluates potential for their implementation in the next generation of advanced, high-performance energy conversion systems.
- **Refrigerant Alternatives Consortium**: explores the potential of alternative refrigerants via experimentation and simulation. Details are described in the following section.
- **Integrated Energy Systems Consortium**: develops a more energy-efficient and environmentally benign approach for building energy supply. The concept of small-scale Cooling, Heating, and Power (CHP) systems operated with natural gas is gaining considerable support very rapidly, and has led to the DOE sponsored CHP initiative that outlines a roadmap to implement CHP technologies in commercial buildings. A full scale test building is being operated on campus
- **Optimization of Thermal System Consortium**: optimizes thermal systems that meet weight, performance, and cost goals. Current projects are the development of an advanced vapor compression cycle simulation tool, a heat exchanger design tool, an accumulator model and software for optimized integrated power generation and waste heat utilization systems.
- **CEETHERM Consortium**: conducts research



[그림 1] CEEE Consortia and Laboratories



towards least-energy data center, including on-site power generation/waste heat utilization while simultaneously integrating electronics cooling down to the chip level. This consortium is a joint research effort with the George Institute of Technology.

- **Reacting Flow Laboratory**: focuses in areas related to catalytic reactor characterization and design for clean energy conversion, dynamic-simulation tools for reactor and system design, and enhanced combustion stability for ultra-low NOx applications.
- **Combustion Diagnostics and Environmental Measurements Laboratory**: develops diagno-stics for control of combustion and industrial processes. Current projects include real-time measurement of multiple species concentrations and temperatures using multiplexed, tunable diode lasers, hazardous waste destruction using molten salt oxidation, laser induced breakdown spectroscopy (LIBS) for real-time measurement of ambient particulate matter, measurements of engine gas-phase and particulate emissions using real-time laser methods, fundamental physics of LIBS for aerosol detection, flame spread over solid fuels in micro-gravity conditions, and simultaneous strain and temperature sensing using fiber optic Bragg gratings.

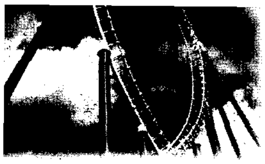
CO_2 Cycle Research Initiatives at CEEE

Continuing environmental concerns, such as global warming and toxicity, still call into question the long-term viability of new HFC refrigerants. Consequently, so-called "natural" fluids that demonstrate a surprisingly strong performance potential have emerged. In 1993 Dr. Yunho Hwang initiated research at CEEE on these long-term alternative refrigerants. Under the initial sponsorship from the U.S. EPA and EPRI, he investigated the performance potential of the transcritical CO_2 refrigeration cycle theoretically and experimentally. The major accomplishments of the research are summarized as follows:

- Extended theory for optimum gas-cooling pressure was suggested.
- Source of CO_2 performance degradation was analyzed in detail.
- New hermetic CO_2 compressor prototype was built.
- Water chilling and water heating performance of CO_2 cycle was demonstrated.
- Heat transfer correlations of boiling and supercritical forced convection for CO_2 were screened and modified to represent available data.
- Heat exchanger models were developed and verified
- Compressor and expander models with ref-rigerant leakage were developed.
- Detailed transcritical CO_2 cycle model was developed.
- Several laboratory prototype transcritical CO_2 cycles were developed.
- Potential of CO_2 as an alternative to R-22 was demonstrated.

Refrigerant Alternatives Consortium

After successful initial study on the transcritical CO_2 cycle, authors started the Refrigerant Alter-



natives Consortium (RAC) in 1997, which focuses on exploring the potential of alternative refrigerants via experimentation and simulation. Its goal is to provide sponsors with the background information necessary to make decisions on refrigerant selection and to provide a head start in component and system design and development.

Current RAC Projects

Current investigations within RAC focus on:
Two-stage CO_2 cycle optimization

- Heat transfer measurements with CO_2/oil mixtures
- Oil retention measurement in CO_2 A/C systems
- CO_2 compressor/expander modeling
- Automotive CO_2 climate control systems
- CO_2 stationary air-conditioners
- CO_2 low temperature refrigeration system
- R32 and HCs as R410A and R22 replacements

Two Stage CO_2 Cycle Optimization

The performance of a CO_2 system can be improved by employing a two-stage cycle. Three different variations of a two-stage vapor compression cycle have been studied by using simplified modeling assumptions. The cycles are a flash cycle, a phase separation cycle, and a split cycle. For each cycle, the potential benefits of utilizing an internal heat exchanger, a suction line heat exchanger, and intermediate cooling between the compressor stages have been investigated. From the model results, a split two-stage cycle outperforms all other options, showing a 38 – 63 % performance improvement over the basic single-stage cycle. Based on model calculations, a split two-stage cycle is a feasible option for improving the efficiency of the CO_2 transcritical cycle. The best cycle option selected from the initial screening is in the process of its experimental verification.

Heat Transfer Measurements with CO_2/Oil Mixtures

A test facility for measurement of heat transfer coefficients with a CO_2/oil mixture has been built. Measurements of CO_2/oil mixtures' boiling and gas cooling heat transfer coefficients and pressure drops in microchannel geometries have been conducted. Currently, the measurements of the gas cooling heat transfer coefficients with a greater number of different oils are underway. CO_2 boiling and gas cooling heat transfer and pressure drop correlations will be developed based on measured data.

Oil Retention Measurement in CO_2 A/C Systems

Previous experimental results leave great uncertainty about oil retention in the system, oil/refrigerant flow patterns, and circulating oil concentration. For that reason, a test facility for the visualization of oil/refrigerant flow patterns has been built. Measurements of the oil retention and the circulating rate in CO_2 air-conditioning systems have been completed. Currently the on-line measurement of the oil-circulating rate in CO_2 air-conditioning systems and the experimental evaluation of effects of the oil-circulating rate on the cycle performance are in progress.

CO_2 Compressor/Expander Modeling

The performance of a CO_2 cycle can be greatly enhanced when an appropriate expander is available. We have initiated a task to develop a compressor/expander model based on our compressor modeling experience. Applications for the simulation method beyond estimating the performance of single components are optimization of the overall cycle performance of transcritical vapor compression cycles using integrated compressor-expander devices and wear analysis on compressors and expanders. The simulation is based on a discretization of the compression and expansion processes including three sources of irreversibility: valve losses, internal leakage, and heat transfer. Different control strategies for the optimization of the high-side pressures of transcritical CO_2 cycles with work-extracting expansion devices (expanders) are under investigation.

Automotive CO_2 Climate Control System

This project focuses on the evaluation and demonstration of the performance potential of a CO_2 automotive air-conditioning system that maximizes simplicity and cost savings. A CO_2 and an R134a automotive air-conditioning system were constructed in order to compare their performances. Both systems are equipped with an evaporator and a condenser/gas cooler of comparable size, and a suction line heat exchanger is utilized in both systems. The evaporating conditions are controlled with variable size expansion devices. Measurements have been carried out over a typical range of outdoor temperatures (25 to 45℃) for idling and driving conditions.

CO_2 Stationary Air-conditioner

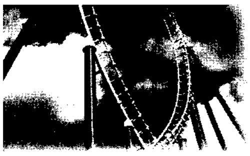
A breadboard prototype transcritical CO_2 environmental control unit was designed and built for the US Army in order to investigate the performance potential of CO_2 in stationary air-conditioning and heat pumping cycles. The characteristics of the compressor in the cycle were of particular importance in this study, and as such, formed the basis for the simulations used to predict the design of the prototype. The evaporator and gas cooler were both constructed using microchannel technology previously tested by the Center, and designed to allow the refrigerant to follow cross-counterflow paths with respect to the airflow direction (in order to maximize effectiveness).

CO_2 Low Temperature Refrigeration System

Applications of the CO_2 transcritical cycle are not limited to medium and high temperature applications such as the air conditioning and water heating. Use of the CO_2 transcritical cycle extends to the low temperature refrigeration as well, with the same motivation to utilize more environmentally friendly alternative refrigerant. Design and experimentation of CO_2 low temperature refrigeration system is currently underway to validate this concept.

R32 and HCs as R410A and R22 Replacements

With increasing interests in flammable refrigerants the need arises to comprehensively and



evenhandedly compare the performance potential of these fluids in typical equipment. We explored the performance potential of R32 and R32-rich mixtures in R410A equipment. Hydrocarbons (HCs) are flammable but have the least GWP. HCs require the design and implementation of significantly different components and systems. HCs have been tested in R22 equipment. Appropriate design changes in components to implement HCs have been made. Extensive experimental tests at various conditions are underway.

Past RAC Projects

Past projects, which had been conducted under the RAC, are as follows:

- Heat Transfer & Analysis:
  - –NH_3 and CO_2 boiling heat transfer coefficient measurement
- Components:
  - –Benefit of suctionline heat exchangers on R134a and CO_2 systems
  - –Implementation and optimization of an evaporatively cooled gas cooler
  - –Hermetic CO_2 compressor design and development
  - –CO_2 compressor life testing
  - –Evaluation of lubricants for CO_2
  - –CO_2 scroll expander prototype development
  - –CO_2 leak detection method development
  - –CO_2 flow visualization
- Systems :
  - –CO_2 water chiller and CO_2 water heater development
  - –Comparison of cycle options for R22, R134a and CO_2
  - –TEWI analysis of automotive A/C
  - –Simulation of CO_2 automotive heat pump system
  - –R32 mixtures performance measurement

Future RAC Projects

The Center will continue its research on future CO_2 transcritical systems while focusing on the following areas.

- Optimization of cycle components and system operation controls : Since the CO_2 transcritical cycle is unique as compared to conventional cycles and is subjected to wide operating conditions, the optimization of cycle components and the development of proper system control strategy are important. The Center will pursue an optimization of cycle components and system operation controls by using simulation and experimentation for each specific application.
- Efficiency enhancement: The biggest challenge of the CO_2 transcritical cycle is efficiency improvement. The Center has identified three major means to enhance the efficiency. They are implementations of the suctionline heat exchanger, two-stage cycle and work extracting expander. The Center plans to expand current research on these subjects.
- Expansion of applications: The CO_2 transcritical cycle has demonstrated its potential and is being mass produced, especially for automotive and water heating applications. The Center will expand its applications into

various refrigeration and air conditioning applications.

Technology Transfer

The Center transfers research results to sponsors in various forms as described below.

Direct Report

Sponsor benefits include availability of heat transfer data, prototype systems performance, and system simulation models. Moreover sponsors have direct access to results from 1997 to the present and to pre-competitive research results that enhance the sponsor's strengths without hampering their competitive positions.

Consortium Meetings

Consortium research results are updated regularly three times a year : in January in conjunction with the ASHRAE Winter Meeting, in March in conjunction with the SAE World Congress and in September at the Center. All progress reports and presentation files are distributed and are downloadable through the CEEE sponsor's website. At the meeting, a vote determines how next research period will be conducted.

Workshops

A variety of workshops has been offered for industry and research sponsors. In 1997, the Center hosted the first International Conference on natural refrigerants, namely "Heat Transfer Issues in Natural Refrigerants," sponsored by IIR. The second workshop was held in 2000 and titled "Vapor Compression Systems with a Critical Point in Mind." Seventy-two researchers and engineers from the U.S., E.U., and Asian countries attended this workshop.

The following list shows thermal system related workshops hosted by the Center since 1997.

- Sorption Cycle Basics and Emerging Sorption Technologies, April 1997
- Heat Transfer Issues in Natural Refrigerants, November 1997
- Vapor Compression Systems with a Critical Point in Mind, February 2000
- Miniaturization of Thermal Systems, April 2000
- The Potential of Cooling, Heating and Power Systems for Buildings, September, 2000
- Miniaturization of Energy Transfer Systems, November 2000
- DOE / CETC / CANDRA Workshop on Microturbine Applications, January 2002

Courses

Through its Graduate Education program, the Center also educates a new generation of creative, team-oriented engineering professionals who will be future leaders in the field of environmental energy engineering. The Center has also introduced new courses in the area of Energy and Environment and Integrated Cooling, Heating and Power Systems.

The Center has offered a class entitled Environmental Engineering (ENME423), which has

topics in Cooling, Heating, and Power Generation (CHP) technology. This is a three-credit senior level mechanical engineering class, which covers CHP technology and equipment. Also covered are heating and cooling load computations, thermodynamics of refrigeration, low temperature refrigeration, and problems involving extremes of temperature, pressure, acceleration and radiation.

Another class is Energy Systems Analysis (ENME635), which is a three-credit graduate level mechanical engineering class. It covers problem definitions using Engineering Equation Solver, vapor compression cycles and conventional power plants, ASHRAE temperature bins, weather data, waste heat utilization, working fluid mixtures, thermodynamic diagrams, generation energy conversion cycles with heat input only, absorption systems, desiccant systems and system integration options.

Visiting Researchers

The Center welcomes visiting engineers from industry and institutions. Since 1991, the Center has invited seven engineers and five professors from overseas.

CEEE Knowledge Base

The CEEE Knowledge Base is a database created from the knowledge and experience gained and collected by the CEEE faculty, students and staff during 20 years of research in the field of distributed energy conversion. Focus areas are properties and heat transfer characteristics of working fluids, thermodynamics, components, heat pumping, air-conditioning, refrigeration and distributed power generation.