ADVANCES IN NON-VAPOR-COMPRESSION REFRIGERATION SYSTEMS

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ABSTRACT

The U.S. Department of Energy is sponsoring several research programs towards developing highly-efficient refrigeration and air conditioning technologies. The Small Business Innovation Research (SBIR) Program is one such research activity.

This paper discusses two SBIR research topics that are advancing the developments of innovative refrigeration and air conditioning concepts. First, the 1989 SBIR research topic on innovative refrigeration systems discusses two Phase II research projects. In one project, Rocky Research is conducting research on media development and experimental verification of an advanced staging concept for high-COP, solid-vapor, heat-actuated, complex-compound heat pumps. In the other project, Stirling Technology Company is developing a prototype of a free-piston Stirling domestic refrigerator using flexural bearings.

Second, the 1991 SBIR research topic on innovative appliances covers seven Phase I research projects. The research includes four projects on advanced heat pumps and three domestic refrigerator projects. The four Phase I advanced heat pump projects consist of an absorption cycles project, a kinematic Stirling heat pump, and two Vuilleumier heat pump concepts. The three refrigerator projects are a kinematic Stirling refrigerator, a metal hydride refrigerator, and a novel vacuum insulation project.

INTRODUCTION

The U.S. Department of Energy (DOE) is sponsoring several research programs towards developing highly-efficient refrigeration and air conditioning technologies. The Small Business Innovation Research (SBIR) Program is one such research activity. Its mission is to promote the research and development of advanced concepts concerning critical energy-related scientific or engineering problems and opportunities that could lead to significant public benefit if the research is successful.

The SBIR program objectives include fostering technological innovation in the private sector, strengthening the role of small business in meeting Federal research and development needs, increasing the commercial application of DOE-sponsored research results, and improving the return-on-investment from Federally funded research for economic and social benefits to the nation. Through this program, many promising concepts and inventions are reduced to practice and result in commercial products that may otherwise remain undeveloped due to the lack of adequate funding.

This paper discusses two SBIR research topics that are advancing the developments of innovative refrigeration and air conditioning concepts. First, the 1989 SBIR research topic on innovative refrigeration systems discusses two Phase II research

projects. They are a solid-vapor, heat-actuated heat pump and a free-piston Stirling refrigerator. Second, the 1991 SBIR research topic on innovative appliances covers seven Phase I research projects. The research includes four projects on advanced heat pumps and three refrigerator projects.

SBIR PROGRAM DESCRIPTION

The SBIR program was established by the Small Business Innovation Development Act of 1982. Typically, the Department sponsors research in over 30 topics through the SBIR program each year. The program consists of three phases. The SBIR program sponsors the first two phases, while private sector financing and non-SBIR Federal funding are used in the last phase. The Department awards around 150 Phase I research grants annually. Typically, about one-third to one-half of these projects will continue on to the Phase II program, depending on Phase I results and availability of program funding.

In Phase I, research is conducted to make progress toward establishing the scientific and technical feasibility of an innovative approach or concept. The intent of this phase includes sponsoring research that assists in lowering the technological risks associated in developing the concept into commercial products. Usually, a Phase I project lasts about six months and costs up to $50,000.

The principal research or R&D phase is conducted in Phase II, in which a proof-of-concept or engineering prototype of an actual system may be designed, fabricated, and tested. Phase II projects may last up to two years and may cost up to $500,000.

SBIR Evaluation Criteria

The SBIR program uses different sets of evaluation criteria for Phases I and II. Then, through independent reviews, the Department awards those proposals judged to be of the highest overall technical merit.

The five evaluation criteria for determining Phase I awards are: the scientific/technical quality of the research; the degree of technical innovation demonstrated in the proposal; the qualifications of the Principal Investigator, key staff, and consultants; the anticipated technical and economic benefits (with special emphasis on the likelihood of attracting private sector funding); and the soundness and level of adequacy of the Phase I proposal toward proving concept feasibility.

The five criteria for Phase II awards are: the scientific/technical quality of the research with special emphasis on its innovation; the qualifications of the Principal Investigator, key staff, and consultants; the anticipated technical and economic benefits (with special emphasis on the likelihood of attracting private sector funding); the degree to which the Phase I objectives were met; and the soundness and level of adequacy of the Phase II proposal to meet the problem or opportunity.

Rights to Data and Patents

According to SBIR rules, the small business retains all rights to technical data resulting from the research conducted in Phases I and II. DOE may use technical data

for its own purposes; but cannot release proprietary data outside the Department for a two-year period after the completion of the SBIR research project without receiving permission from the small business. However, DOE retains a royalty-free license to use technical data obtained in SBIR projects.

As all of the research projects reported in this paper are ongoing, much of the information is still proprietary. It may not be disclosed. Consequently, some of the descriptions discussing the research projects reported in this paper are intentionally brief to comply with the restrictions on data rights.

Typically, the small business retains principal worldwide patent rights to all inventions developed under the SBIR program. However, DOE does retain a royalty-free license for its own use and, in certain circumstances, reserves specific march-in rights and may require the patent holder to license others. Finally, anyone exclusively licensed to sell the invention is encouraged to manufacture it domestically.

1989 SBIR TOPIC ON INNOVATIVE REFRIGERATION SYSTEMS

The 1989 SBIR topic on innovative refrigeration systems was seeking research for innovative approaches and novel concepts that could lead to more energy-efficient, economical, and environmentally acceptable use of refrigeration and air conditioning systems. Technical innovation related to novel refrigeration processes or approaches may result in energy savings of up to 40 percent. In the buildings sector alone, an estimated three quads of energy could be saved. Accordingly, research proposals were submitted on novel working fluids for vapor compression processes, novel working fluids for absorption processes, novel thermodynamic concepts and cycles, and advanced components.

There were eight Phase I contracts in this topic. Two of these contracts were continued through Phase II. The Phase II contracts are a solid-vapor, heat-actuated heat pump and a free-piston Stirling refrigerator. They are discussed below. The remaining Phase I projects covered improved working fluids for absorption cycles, a novel absorption-cogeneration cycle, a novel modulating reverse-Ericsson machine, a metal hydride heat pump, an electrocaloric refrigerator, and a thermally driven heat pump refrigerator. Due to the high quality of other Phase II proposals and limited program funding, these six projects were not funded in Phase II.

Solid-Vapor Heat-Actuated Heat Pump

Rocky Research is conducting research on media development and experimental verification of an advanced staging concept for high-COP, solid-vapor, heat-actuated, complex-compound heat pumps. In this project, an innovative staging concept for a complex-compound heat-actuated heat pump was studied. As the staging was done in only two pressure levels, no excessively high or low pressures were encountered. The concept resulted in high COPs when ammonia or water were used as the refrigerant.

Under Phase I, industrial refrigeration systems, commercial chillers, and industrial heat pump water heaters were determined to be the most promising applications for this concept. For Phase II, hydrated complex compounds are being synthesized for various stages of the staging concept. Proof-of-concept experiments are being conducted

emphasizing the heat recuperation between stages in the heat engine part of the cycle. Successful development of this concept through Phase III could result in the development of a commercially viable, highly efficient, heat-actuated heat pump for the commercial chiller market or other selected markets. This will then lead into development efforts into other markets, such as industrial refrigeration, heat pumps, and air conditioners.

Free-Piston Stirling Refrigerator

Stirling Technology Company is developing an innovative Stirling cycle household refrigerator using flexural bearings. In this project, a prototype of a free-piston Stirling refrigerator is under development. Under Phase I, a conceptual design was completed. It indicated that the Stirling refrigerator could be efficient, reliable, and have a low manufacturing cost.

In Phase II, further design improvements were made that increased the overall efficiency and reduced the size and weight of the Stirling unit. Figure 1 shows a detailed diagram of the Stirling unit, where the linear motor is on the bottom and the Stirling cooler is on the top. After testing of individual subassemblies, such as the linear motor, the heat acceptor and rejector, and flexural bearings, testing of the prototype Stirling refrigerator was conducted to map its performance over a wide range in operating conditions. Preliminary results indicate that the performance of the prototype Stirling refrigerator may compete favorably with current refrigerators using CFCs. Figure 2 shows the prototype unit being bench tested in which frost has formed on the heat acceptor on top of the unit.

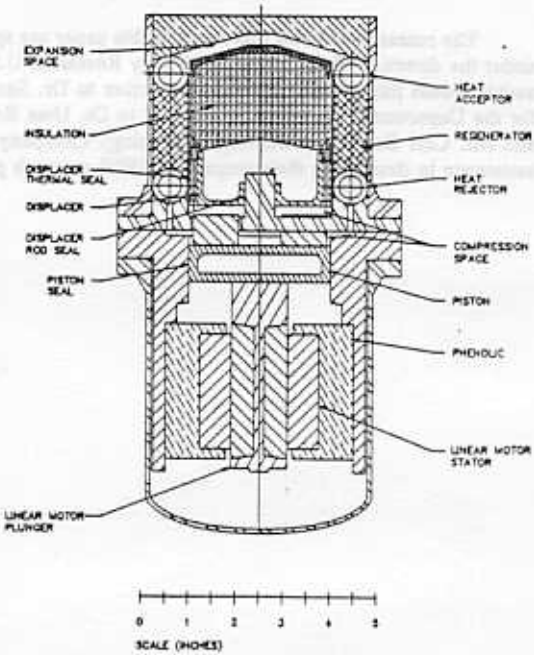

Figure 1. *One of several Stirling domestic refrigerator concepts now under development by the U.S. Department of Energy.*

1991 SBIR TOPIC ON INNOVATIVE APPLIANCES

The 1991 SBIR topic on innovative appliances noted that recent technological advancements can offer significant energy savings if they can be incorporated innovatively into electrical appliances. Types of appliances considered include

rel ators, water heaters, clothes washers, and dishwashers, as well as integrated appliances and heating and air conditioning equipment. In this SBIR topic, DOE was seeking innovative approaches and novel concepts that could lead to more energy-efficient, economical, and environmentally acceptable use of these common appliances. Such approaches may have the potential of reducing energy consumption by at least 30 percent--potentially saving as much as four quads of energy per year in the U.S.

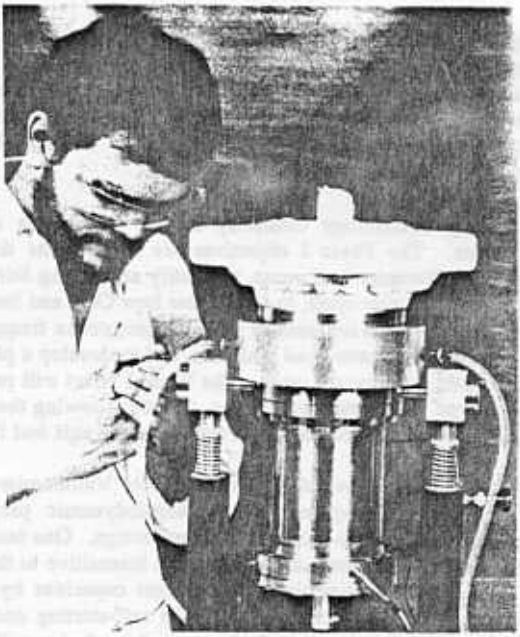

Figure 2. *A DOE-developed, free-piston Stirling refrigerator being tested for performance.*

Research proposals were submitted on advanced appliance concepts, non-vapor compression refrigerators, novel heat pumps, and advanced components. Ten Phase I research grants were made. Four projects on advanced heat pumps and three refrigerator projects are described below. The remaining projects were on advanced appliance concepts. They are not discussed in this paper.

Advanced Heat Pumps

The four Phase I advanced heat pump projects include an absorption cycles project, a kinematic Stirling heat pump, and two Vuilleumier concepts. TDA Research, Inc. is conducting research on improved absorption cycles. They are investigating the performance advantages of a unique refrigerant/absorbent pair which exhibits a potential for higher COPs than currently known absorption fluids. The Phase I research will measure the properties for this refrigerant/absorbent pair and will use experimental data to carry out cycle analyses to evaluate the performance improvement for the new system. In Phase II, additional promising refrigerant/ absorbent pairs will be investigated to optimize the absorption cycle. Then, a three-ton prototype absorption machine will be built and tested to experimentally confirm the performance benefits.

Stirling Technology Company is developing a free-piston, Stirling-cycle unitary heat pump. They will develop and test a proof-of-principle demonstration model of an electrically-driven Stirling-cycle heat pump. The proposed concept will use a free-piston/linear alternator concept using flexural bearings as a low cost alternative to gas bearings. The Phase I objectives are to select a target size for the proposed system,

develop a detailed set of specifications for the proof-of-principle unit, develop and refine a conceptual design, and project the performance of the unit over the range of operating conditions developed in system specifications. Phase II objectives are to complete the detailed design and subcomponent drawings, fabricate components, assemble the system, and carry out an extensive test program to evaluate both system performance characteristics and hardware durability.

Stirling Technology Company is also developing a Vuilleumier heat pump demonstrator. The Phase I objectives are to optimize the design of a conceptual residential Vuilleumier heat pump, to modify an existing Stirling-cycle analysis code to model the Vuilleumier cycle, to investigate how COP and loss mechanisms are affected by heat exchanger and regenerator technologies, stroke frequency limitations of welded metal bellows, and heater head materials, and to develop a performance map of the unit over a realistic temperature range. The Phase I effort will produce a conceptual design for a prototype Vuilleumier heat pump, thereby, allowing the Phase II effort to focus on the detailed design, fabrication, and testing of the unit and its components.

Creare, Inc. is developing an innovative Vuilleumier heat pump. The Phase I effort will focus on optimizing the thermodynamic parameters and the physical configuration of the heat-driven heat pump design. One innovative feature is an array of small parallel heat pump cells, making it insensitive to the failure of any individual cell. This design enables sizing to different capacities by adding or subtracting the number of cells. The heat pump will be self-starting and self-driven, requiring no electrical parasitic losses. A preliminary machine design will be made. Its performance will be evaluated from both a technical and economic aspect. The Phase I effort will define fabrication methods and the conceptual design for the prototype Vuilleumier heat pump to be fabricated and tested in the Phase II effort.

Refrigerators

The three refrigerator projects are a kinematic Stirling refrigerator, a metal hydride refrigerator, and a novel vacuum insulation project. Stirling Technology Company is developing a kinematic-drive Stirling-cycle refrigerator. Key issues to be investigated are the development of a high-efficiency Stirling-cycle refrigerator operating over the required temperature range, the implementation of metal-bellow seals for long-life dynamic seals, the development of an efficient, low-temperature, heat-transport system to move heat from the refrigerator to the heat acceptor of the Stirling unit, the development of a similar heat transfer system to move heat from the heat rejector of the Stirling unit to the ambient environment, and the development of an efficient and cost-effective design. Phase I objectives are to develop an overall conceptual design, evaluate the performance characteristics over a range in sizes and capacities, and develop a basic layout of a proof-of-principle prototype. Phase II objectives are to complete the detailed design, fabricate, assemble, test, and evaluate the performance of the prototype kinematic Stirling cycle refrigerator.

Thermal Electric Devices, Inc. is developing a metal-hydride refrigerator, in which hydrogen is absorbed and desorbed between two different metal hydrides. Previous research has not found any metal-hydride system which could compete with vapor-compression systems. However, this project will develop an innovative design which may exceed the performance of vapor-compression systems. In Phase I, a laboratory

working model of the innovative metal-hydride refrigerator will be tested to demonstrate technical feasibility.

Vacuum Energy Inc. is developing an innovative superinsulation for refrigerators. The Phase I goal is to demonstrate the novel superinsulation concept capable of achieving insulating values of at least R-20 per inch, with upside technical potential of R-40 per inch. Even though this concept may not exceed the performance of the best vacuum insulation concepts, this novel superinsulation is considered to have superior life properties and better price-to-performance characteristics than many currently known advanced vacuum insulation concepts, such as multi-layer vacuum systems, powder insulations, and aerogels.

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