STIRLING AND VUILLEUMIER HEAT PUMPS

Design & Applications

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Stirling and Vuilleumier Heat Pumps

Dedicated to my parents, who gave me their unselfish guidance through their difficult lives.

JAROSLAV WURM

Dedicated with love and appreciation to my wife, Barbara, who supported me and gave me the time to develop these numbers, words, and pictures, and to God who made everything we explore.

JOHN A. KINAST

Dedicated to my loving wife, Rosmarie, and my caring children, Sarah, Robert, Peter, and Laura, who give purpose to all I do.

THOMAS R. ROOSE

Dedicated with love and appreciation to my wife, Ann, and to my children, Meredith and Andrew.

WILLIAM R. STAATS

Preface

There is widespread concern that the use of fossil fuels has been too profligate. Fears of fossil fuel depletion pervaded much of the 1970s and 1980s. Now we are beginning to learn that our use of fossil fuels is producing carbon dioxide faster than the atmosphere and oceans can accommodate it.

With no complete substitute at hand for fossil fuels, it is increasingly important to use them as effectively as possible. This book approaches one aspect of that use: heating and cooling of occupied buildings. The use of energy for space conditioning or comfort heating and cooling is now considered a necessity in most industrialized countries. In the United States, space conditioning accounts for about one-third of all the fossil fuel consumed for purposes other than transportation. Fuel use for space conditioning could be reduced substantially if heat pumps, with their substantial efficiency advantages, were more widely used.

The term heat pump is used throughout this book to describe the combination of the driving unit, or engine, and the energy consuming device, or refrigerator, which absorbs heat at a lower temperature and discharges it at a higher temperature. Heat pumps are used for both heating and cooling. Strictly speaking, the electrically driven heat pumps used to heat and cool buildings only fit the above definition of complete heat pumps when the large engine at the electric power station is considered a part of them.

This book deals with six examples of engine-driven heat pumps. Both the engine segment and the refrigerator segment of these heat pumps are based on Stirling cycles or similar thermodynamic cycles. Stirling-cycle external combustion engines, in principle, offer higher efficiencies and better maintenance characteristics than internal combustion engines. Stirling refrigerators also have potential performance benefits. These heat pump combinations are not commercially available; and, for some of them, prototype equipment has not even been built. They all need further development, particularly to reduce their cost. However, they all have one important characteristic that can lead to cost reduction. They combine the engine and refrigerator segments and share components between them. This intermingling of the engine and refrigerator functions leads to the term *integrated heat pump,* which is used throughout the book.

Many combinations of different engines and refrigerators are possible, and the ingenuity of several inventors has resulted in the development of many different prototypes. None of these prototypes have entered commerical production. The perceived advantages of the new designs have not yet been impressive enough to overcome the large capital investments required for mass production. To convert a promising idea into effective prototype hardware is costly, both in R&D funds and time. The R&D would cost less if we could calculate the potential performance of the prototype equipment and critically compare it to other configurations before building it. Such an analysis could also suggest better configurations and help in prototype design by showing how certain components limit system performance. This would allow the designers to balance performance improvement against the cost of better components.

Unfortunately, integrated heat pumps have not received the same comprehensive literature coverage as similar concepts with separate cycles that are linked mechanically or electrically. The technical literature does not contain much information on integrated heat pumps, and most engineers are not familiar with their analysis. Furthermore, the few engineers who are experts in this field have evolved detailed analyses of the performance of the specific equipment concept they are developing. Although these mathematical models are precise, they do not allow even-handed comparison with other concepts. This makes it difficult to choose objectively among the various concepts that have been proposed.

We intend to help remedy that situation by documenting consistent methods for analyzing the performance of this equipment. We focus on six concepts that integrate the engine and refrigeration cycles, all based on Stirling, Ericsson, and Vuilleumier cycles. The six heat pump concepts are examples of how to apply the analysis methods. In addition to comparing the performance of these concepts, the analytical methods give inventors and designers a way to quantitatively predict the performance capabilities of new systems and their components. Such evaluation can also lead to more confident R&D decisions through better assessment of the potential success of specific configurations. For the configurations that warrant substantial R&D, the techniques will improve the design of prototype equipment. Ultimately, we hope our readers will use the methods presented to devise even better integrated heat pump concepts.

A brief survey of engine-driven heat pump technologies in Chap. 1

delineates the scope of this book. It explains the usefulness of engine-driven heat pumps in general and integrated heat pumps in particular. Chapter 2 describes the thermodynamic basis for analyzing heat pump performance, and Chap. 3 extends that basis and applies it to heat pump concepts that integrate the engine and the refrigerator. Chapter 4 explains the factors that are important for commercial success of a heat pump concept and how these factors affect the selection of concepts for development. It also illustrates the advantages of the six specific embodiments of integrated heat pumps, which will be analyzed in subsequent chapters. Chapter 5 describes these six embodiments more fully and explains why we selected them for analysis. Chapter 6 outlines many of the methods that others have used to analyze Stirling cycle equipment performance and the methods used in this book to analyze integrated heat pump performance. Chapter 7 gives the results of our comparative analysis of the six embodiments. Chapter 8 adds a description of equipment that is now under development and outlines the analysis of components, such as heat exchangers, which are particularly important to the performance of integrated heat pumps.

Appendices A through E contain documentation and listings of the computer programs used in the analysis whose results are reported in Chap. 7. These programs define exactly how the analysis was performed, and they will be a guide to others who want to analyze similar integrated heat pump concepts.

Appendix F documents an example of a computer program that extends the above analyses to predict how realistic heat exchanger design affects heat pump performance, as described in Chap. 8. Mr. Marek Czachorski developed the program shown in Appendix F and the performance calculations shown in Chap. 8. We appreciate his consent to use them here.

This book stems from research performed at the Institute of Gas Technology, funded by the Gas Research Institute. We are grateful for the cooperation of these companies in allowing us to include the results of this research. We also appreciate the help of those researchers and companies who have produced research and prototype machines of practical value. Several of them gave us permission to describe their equipment and activities in this book. Without these contributions from Philips Research Laboratories, Sunpower, Inc., the University of Dortmund, the University of Munich, Professor Franz X. Eder, and Tokyo Gas Company, this book would have only academic interest.

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Contents

Chapter

1

Introduction

Ventilation and ice storage were the only available ways to cool buildings until the mid-nineteenth century. The invention of a variety of engines which could drive refrigeration systems in the nineteenth century made space cooling technically possible, but practical prime movers (engines and electric motors) were not available until the twentieth century. By then, electric power generation and distribution systems had developed to the point where they could dominate space-cooling technology. Even now, the lower costs and maintenance requirements and greater convenience of electric motors usually outweigh the higher cost of electric energy.

For most of the world's population, comfort space conditioning is still limited to fresh air ventilation and heating of the living and working environment by combustion equipment. Yet, world opinion reflects increasing concern over the cost—both economic and environmental—of fossil fuels. There is an increasing desire to meet space-heating needs by more efficient fuel use. In principle, heat pumps offer the prospect of efficiencies that cannot be matched by any other means. The technology developed for comfort cooling has been adapted for comfort heating of buildings. Like cooling equipment, these heat pumps also use electric power.

Although electric power dominates this technology, the potential advantages of alternative power sources still intrigue the research community, and research and development (R&D) is continuing on small engines and other approaches. Much of this R&D has been well covered in the literature, but one important segment—integrated heat pumps based on Stirling, Ericsson, and Vuilleumier cycles—has not. This book provides a consistent description of this family of alternative cooling and heating concepts and methods for analyzing their performance. We hope that the availability of this information will encourage others to consider this potentially important class of equipment when developing new concepts for practical heating and cooling systems.

Engine-Driven Heat Pumps

As early as 1853, Sir William Thomson, Lord Kelvin, derived and documented the fact that engine-driven heat pumps could be designed.[1] In articles published in the *Cambridge and Dublin Mathematical Journal*, this great thermodynamicist described the use of an engine-driven heat pump and calculated its efficiency advantage over simple combustion. The mechanics of his concept may not have been practical, but his prediction of its potential usefulness was prescient. Although the heat pumping principle has been understood for well over a century, most buildings are still heated by combustion, with an efficiency well below 0.9. Commercially available vapor-compression heat pumps driven by electric motors offer better heating efficiencies for a range of conditions. They have disadvantages and limitations, but they are still an important step toward reaching the space-conditioning performance potential envisioned by Lord Kelvin.

Small engines at the building being heated can be an attractive alternative to electric power, which, in essence, uses a large engine at a central electric power station. The exhaust heat from a local small engine can augment the heat pump output during the heating season. In climates with significant heating loads, the annual fuel use for heating and cooling combined can be lower with heat pumps powered by small engines than with those powered by electricity. To be practical, however, this requires small engines which are efficient enough, are inexpensive, and have reasonable maintenance requirements. The engines must also have a far longer life than is normally required in vehicles. Most commercially available internal combustion engines meet these requirements only in sizes well above those needed for residences and small commercial buildings. However, those buildings are important because, in total, they consume much of the energy used for space heating.

As early as the 1930s, attempts were made to develop small-engine-driven air-conditioning and heat pump equipment. The Coleman Company field-tested such equipment in 1956, but it never reached the market. However, the recent remarkable diversity in new prime mover development has led to the development of many new engine-driven heat pumps covering a range of sizes. This worldwide activity has resulted in some successful marketing of residential and small commercial-size units in Japan and larger commercial-size units in Germany.

External combustion engines hold the promise of circumventing the disadvantages of small-engine-driven heat pumps. External combustion engines can have inherently higher efficiency than internal combustion engines, and their heat-rejection characteristics are amenable to recovering the exhaust heat for space heating. External combustion engines can have longer life and need less maintenance because the products of combustion do not contaminate the engine's internal working surfaces. The invention and initial reduction to practice of external combustion engines, originally called hot-air engines, predates that of their internal combustion counterparts, but eventually internal combustion engines supplanted them. The supporting technology needed for efficient, competitive external combustion engines was not available at the turn of the twentieth century, when engine development for automobiles was in its formative stage. Achieving high efficiency and adequate power from external combustion engines requires heat-exchanger designs and construction materials that only recently became readily available. In particular, a lack of materials that allow high-temperature heat inputs has been a critical limitation.

A heat pump needs a refrigerator as well as an engine. Ordinary open-shaft vapor-compression equipment would seem to be the best choice because it is already developed and has been accepted in commercial applications. However, coupling this refrigerator with an engine leads to high overall equipment costs. In most applications, the lower operating costs of such a system do not compensate for the higher equipment cost. This is a compelling reason to look into other engine options (such as the external combustion engines mentioned above), other refrigerator concepts, and, ultimately, novel combinations of engines and refrigerators.

Open-shaft vapor-compression refrigerators are not the only refrigerators that can be used in engine-driven heat pumps. For example, refrigerators which use a working fluid that does not change phase, such as air, offer advantages in cost, performance, and environmental acceptability. Stirling and Vuilleumier heat pumps are in this category; but, despite their potential advantages, there is only limited commercial experience with their use.

Some refrigerators whose working fluids do not change phase could be attractive for comfort heating because of their inherently high potential efficiency over a wide range of outdoor temperatures. Their disadvantage is that achieving such efficiency requires high-performance hardware with many components. The high cost of this complex hardware has prevented widespread application of this type of heat pump, so cost reduction is very important. A first step in reducing costs would be to simplify the hardware by combining component functions, and the most obvious candidates for combination are the heat exchangers. Another simplification is to integrate the engine function with the heat pump function, eliminating power-transmitting equipment. One simpler combination is known as the Vuilleumier heat pump, named after its inventor, who received U.S. patents in 1917 and 1918.[2]

Reference Cycles

The above discussion described engines and refrigerators in broad, general terms. However, the following chapters require a fully developed thermodynamic frame of reference for comparative analysis of integrated heat pumps. This section covers the same concepts as the previous section, but uses more formal categories and specific, precise definitions based on thermodynamic reference cycles. We begin to develop this frame of reference here and continue the development in Chaps. 2 and 3, defining all the cycles of potential interest and eliminating from consideration those that have either proven impractical or are well described in the literature. However, this book does not teach basic thermodynamics. The reader should already understand the basic thermodynamic cycles which, at least in theory, describe both power-producing equipment (engines) and power-consuming equipment (refrigerators). Readers who are not familiar with the common power cycles should consult general thermodynamics texts.[3,4]

Two categories of cycles are described below: those in which the working fluid changes phase from gas to liquid, and those whose working fluid remains in the gas phase. The former are commonly known as *vapor-compression cycles*. The cycles referred to apply to both engines and refrigerators.

Cycles Based on Two-Phase Working Fluids

When working fluids change phase during a cycle, they offer a closer approach to isothermal operation and they carry more energy per unit of fluid circulated than single-phase fluids. This is why equipment using vapor compression, or two-phase working fluids, dominates refrigeration technology. This equipment follows the Clausius-Rankine and Lorenz cycles. We will not analyze vapor-compression equipment because methods for analyzing its performance are freely available in the literature.

Clausius-Rankine machines which combine the engine cycle with the refrigeration cycle, using steam as the working fluid, have been proposed. They have been used in industrial refrigeration or process (noncomfort) air conditioning, and a few have reached commercial application. They are usually steam-turbine-driven vapor-compression machines (piston, screw, or turbine). Those steam-turbine machines that could be used for comfort air conditioning are still under development, and literature references to them are scarce. The most interesting ones use a single fluid in a double-loop configuration. The first designs were based on reciprocating piston expanders and compressors, but recent, more successful R&D has focused on turbomachinery.[5]

Another cycle that describes condensing working fluids, the Lorenz cycle, is becoming more important. Although it is not as well known as the Clausius-Rankine cycle, it actually gives a better description of the operation of vapor-compression equipment. It also allows better representation of cycles that use mixtures of working fluids. This cycle is also fully described in the literature.[6,7]

The Clausius-Rankine and Lorenz cycles are described in more detail in Chap. 3.

Cycles Based on Single-Phase Working Fluids

More theoretical thermodynamic reference cycles and heat pump concepts are based on gaseous working fluids than on working fluids that change phase. Phase-change machines follow only the Clausius-Rankine and Lorenz cycles. Machines operating without phase changes most commonly include Otto-, Diesel-, Brayton-, Ericsson-, and Stirling-cycle concepts.

This book does not include analyses of Brayton, or gas turbine, cycles. (These are referred to as Joule or Ericsson cycles in Europe, but they are not related to the Ericsson cycles described in this book, and the reader should be careful to avoid being misled when consulting European literature.) There are no Brayton-cycle turbines in the size range of interest, and low-cost positive-displacement equipment for Brayton cycles has not been developed. Because of their lower efficiency, simple Brayton-cycle heat pumps offer no performance advantage to compensate for the equipment cost. Brayton-cycle concepts which use regenerative heat exchange could have higher efficiency levels, but with the penalty of higher equipment costs.

Many engineers understand engine concepts based on the Otto, Diesel, and Brayton cycles, since much effort has gone into developing and refining their physical embodiments in cars, trucks, jet engines, and electric power generators. Brayton-cycle refrigerators are widely used in commercial aircraft, where they have easy access to large amounts of fresh, pressurized air. Also, their low weight offsets their inherent low efficiency. As with Clausius-Rankine equipment, a wealth of literature is available for analyzing their performance.

Practical embodiments of Otto- and Diesel-cycle refrigerators have not been conceived.

Most engineers do not understand the design of equipment based on Stirling cycles and the related Ericsson and Vuilleumier cycles because these cycles have not been in the mainstream of practical applications. Although engines based on Stirling cycles have been developed, heat pump and refrigeration applications of these cycles have not been given much attention. Their analysis is also far more complex, as explained in later chapters. However, they have some characteristics that make them potentially desirable alternatives in specific niches. This book focuses on one of those niches: small heat-powered heat pumps.

Stirling-cycle heat pumps have been commercially successful in cryogenic applications, where they have distinct technical advantages over other practical technologies. However, they have not yet been successful in comfort heating and cooling situations, which have temperature ranges of about −20 to 60°C (− 5 to 140°F). As a result, comparative analyses of their performance in comfort heating and cooling configurations are not readily available in the literature.

Concepts that integrate the engine and the refrigerator are, by far, the least understood. The integration itself is important. Analysis of only the separate basic cycles would indicate that the combined performance is equivalent. However, some losses necessarily occur when the power and refrigeration cycles are combined, and only an analysis of the actual performance of practical components shows the differences among the concepts.

Of the cycles mentioned above, only the ideal Stirling and Ericsson cycles are equivalent to Carnot cycles in thermodynamic efficiency. (See Chap. 2 for definitions.) However, we have not selected them for analysis solely because they have maximum thermodynamic efficiencies. Such ideality of one cycle is not a good *a priori* reason to exclude other cycles from consideration. Analysis of ideal cycles, such as Stirling, Ericsson, and Carnot, will indicate that their thermodynamic efficiencies are equivalent. However, the losses that necessarily occur in their real embodiments and through interactions of the power and refrigeration cycles lead to significant differences among them. Conditions of operation may differ, and equipment based on nonideal cycles could actually be more effective than that based on ideal cycles. Furthermore, efficiency is not the only important factor. Other factors which are important in practical systems are described in Chap. 4.

In summary, we analyzed integrated heat pump concepts based on Stirling and Ericsson cycles not only because of their thermodynamic ideality, but also because there are equipment concepts based on these