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THE ROLE OF THE VAPOR COMPRESSION CYCLE IN SOLAR ENERGY UTILIZATION*

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ABSTRACT

The vapor compression cycle lends itself to solar energy utilization in two important ways. Its ability to utilize a relatively low temperature heat supply to produce space heating via heat pumps allows the use of solar input to the evaporator to provide potential Coefficients of Performance which are 2 to 3 times higher than present electric driven heat pumps, and the use of relatively inexpensive solar collectors is possible since the collection temperatures can be low grade. Secondly, the compression process of the vapor cycle can be powered by a solar-driven heat engine, typically using a Rankine cycle, for solar cooling purposes. Discriminating coupling of solar with vapor compression allows the well-developed technology and manufacturing capability of the vapor compression industry to be brought into play in the solar field, widening its base and promoting its diversification.

This paper overviews the cycle thermodynamics, potential practical hardware, and R&D projects in both of these areas. Particular attention is given to the Solar Assisted Heat Pump and its characteristics and the heat pump simulator activities at Brookhaven National Laboratory.

1. INTRODUCTION

The thermodynamic cycle known as the vapor compression cycle is characterized by its ability to move heat from a low temperature reservoir to a higher temperature one. To accomplish this, work must be input, as required by the Second Law, and devices which are reversed heat engines generally known as heat pumps are used. Space conditioning in the form of either heating or cooling is produced depending on whether the low temperature reservoir or source (cooling) or the high temperature reservoir, or sink, (heating) is in the space to be conditioned. The work input is less than the useful heat quantity and a multiplying effect, denoted by a Coefficient of Performance, results.

Solar energy can be utilized to advantage in the heat pump/refrigeration cycle in two principal ways. First it can serve as a heat source which is high by heat pump standards, though low in solar terms, for the evaporating process in the heating mode. The resulting work inputs required are low, producing very efficient cycle COP's which are potentially 2 to 3 times higher than current values. This application is salient for electrically driven heat pumps, and although solar energy is directly used only in the heating function, cooling mode performance can be abetted by opportunistic use of the solar system components. The second method is to drive the compression process of the cycle with a heat engine powered by solar thermal energy. This is typically accomplished by a Rankine or modified Rankine power cycle and has its principal usage in the cooling task, but can also be used for heating.

Discriminating combination of solar energy with vapor cycles is one of the more promising avenues to the difficult goals of cost effective and energy conservative solar space conditioning. This coupling allows the well-developed technology, manufacturing, and distribution capabilities of the vapor compression industry to be brought into play in the solar field, thus widening its base and promoting solar diversification. This diversification effect is more pronounced when it is noted that the level of technology involved spreads in either direction from that of basic electric-driven air conditioner/heat pumps. That is, toward the lower technology side, the use of the relatively low solar-supplied temperatures required 283-311°K (50-100°F) as heat pump input permit the use of low temperature, simple collectors which can be manufactured significantly more inexpensively, and diffusely than collectors which must heat a building directly. On the high technology side, the more sophisticated "aerospace" type of technology is introduced on a decentralized basis via Rankine systems and their turbomachinery, which while unquestionably costly at present, can potentially fuse with the demands of meeting a mass consumer market to provide viable systems over the long term.

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DISCLAIMER

2. THE VAPOR CYCLE AND SOLAR ENERGY

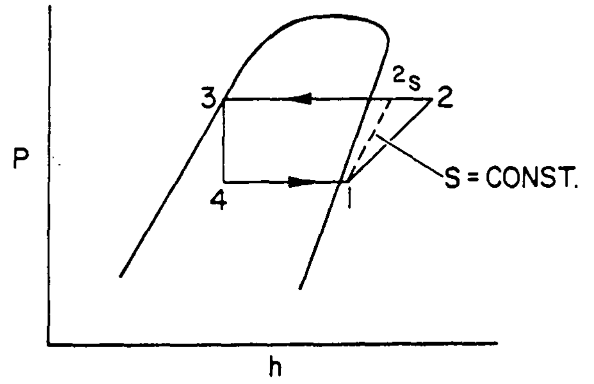

Fig. 1. Basic Vapor Compression Cycle

The basic vapor compression cycle is pictured on the pressure-enthalpy diagram of Fig. 1. In the heating mode, the useful energy derived per unit mass of the working fluid is $h_{2s} - h_3$ for an Ideal Vapor Cycle. The ideal work input by the compressor is $h_{2s} - h_1$, and the COP is:

$$\mathrm{COP} = \frac{h_{2s} - h_3}{h_{2s} - h_1} \tag{1}$$

The actual work input is $h_2 - h_1$, a larger value, due to irreversibilities in the compression process (indicated by the compressor isentropic efficiency); and there are a number of other sources of efficiency loss in the actual vapor cycle which further lower the COP from ideal - including pressure drops, heat losses, prime mover efficiency and those due to practical measures necessary to produce a viable device. In either case, the amount of work input required for the compression process depends on the difference between the condensing temperature, T_3, and the evaporating temperature, T_1, since the compressor must produce a pressure ratio equal (approximately) to the ratio of the corresponding saturation pressures. For a given condensing temperature required for heating, an increase in evaporator temperature causes a decrease in compressor work required per pound of working fluid (refrigerant) and a corresponding increase in COP. The limiting maximum COP obtainable between temperatures, T_3 and T_1, is the Carnot cycle COP given by:

$$\mathrm{COP}_{\mathrm{max.,\ heating}} = \frac{T_3}{T_3 - T_1} = \frac{1}{1 - \frac{T_1}{T_3}} \tag{2}$$

where the temperatures are in absolute units. The Carnot COP is plotted against evaporating temperature for a constant condensing temperature of 322°K (120°F) in Fig. 2. Also plotted is the COP for the Ideal Vapor Cycle, 1-2s-3-4 in Fig. 1, for refrigerants R-12 and R-22 (they are very close in the Ideal Cycle). The latter curve is below that of Carnot primarily because the expansion process is at constant enthalpy, rather than being the isentropic one of the Carnot Cycle. It is clear that both COP curves increase significantly with evaporating temperature, and, moreover, the slope increases with increasing temperature. Herein lies the motivation to introduce solar energy into a heat pump cycle as the heat source, since it can provide temperatures well in excess of those available from ambient air during a heating season and concomitant instantaneous and seasonal COP's which are greatly increased.

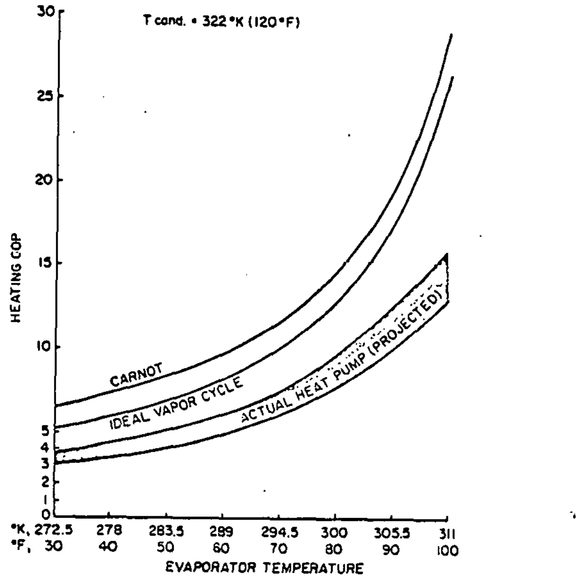

Fig. 2. Heat Pump COP vs Evaporator Temperature

Direct solar heat input makes use of a natural renewable resource as an extension of the traditional search by heat pump applications engineers for a suitable site-specific earth or water source/sink; but herein the potential COP gains are much greater and the source is universal. As in any other solar system, the solar heat input is not "free" because a system to collect it must be paid for; but because the input temperature range of importance, 277 to 311°K (40 to 100°F) is low for solar, the use of collectors or collector-like devices which are significantly less costly per square foot than direct heating collectors is allowed.

Given the theoretical incentive, applying this approach requires utilizing a vapor cycle machine that will follow the monotonically increasing COP trends of the Carnot and Ideal Vapor Cycle at the lower level of practical hardware. Two aspects of attaining this potential must be treated—those producing good, energy efficient component performance for any refrigerator/heat pump and those which specifically provide extension of this performance to high evaporator temperatures of solar input, as will be discussed later. In Fig. 2 the potential performance which can be obtained by meeting these aspects satisfactorily is given by the shaded band. It was developed by examining operating data for current efficient heat pumps and compressors in the evaporator temperature range up to 283°K (50°F) and performing calculations to obtain component efficiencies which were extrapolated to project performance into the range above 283°K. Heat exchangers large enough to accommodate the heat loads at all temperatures were assumed, and a nominal electric motor efficiency of .85 was used.

The second principal application of solar energy to a vapor cycle is the use of a solar-driven heat engine to produce the compression work for a vapor compression cooling system, and it is one of the relatively few viable techniques which can produce cooling from solar input. This method would not be used to principally drive the heating mode since it is obviously more effective to utilize thermal input directly, and the heat engine suffers from nature's trait that makes it easier to convert work to heat than heat to work. Once present for the cooling task, however, the heat engine/VC system can also be applied to space heating, i.e., be a heat pump, in order to improve potential for cost effectiveness; and in the heating mode, the evaporator of the VC loop can use some of the collected solar energy to improve COP.

The solar input to drive a heat engine requires collection at temperatures which are high by solar standards, since Carnot limitations demand as high a cycle temperature as possible for reasonable power loop efficiency. The Carnot limiting efficiency for a heat engine operating between a temperature, T_h, and a lower one, T_c, is:

$$\eta_{Carnot} = \frac{W_{out}}{Q_{in}} = \frac{T_h - T_c}{T_h} = 1 - \frac{T_c}{T_h} \qquad (3)$$

where T_c is the rejection temperature which must be above ambient in a practical device. Thus, high grade collectors which can produce temperatures far above ambient and still attain good efficiency are required; but the fact that higher collection temperatures produce lower collector efficiencies can cause a trade-off to be made with cycle efficiency. The most important factor in a system of this type, though, is to raise cycle efficiency in order to reduce collector area, since collectors are by far the most costly system element. This basically implies higher cycle temperatures.

Current and near-future collectors can reach 422°K (300°F), at most, with any reasonable efficiency, and at this temperature limit the Rankine cycle type of heat engine, which incorporates a liquid to vapor phase change, has received the major development attention rather than gas cycles which need higher temperatures to be effective. Development of concentrating collectors which give temperatures in the 533°K (500°F) range could permit a broader choice of solar heat engines.

A technique to increase Rankine cycle efficiency substantially is the use of a fossil-fuel fired superheat of a working fluid that has been vaporized by solar input at 250-300°F. This "topping cycle" can be used to meet the design cooling load but requires only a relatively small fuel input over the course of a season, compared to the solar input to the latent heat. If water is used as the working fluid, a superheat temperature of 1000°F can be used, doubling the Rankine efficiency and halving the required collector area.

3. SOLAR ASSISTED HEAT PUMPS

Even at this early stage of solar utilization, there has been considerable interest in combining solar energy with heat pumps. A number of ad hoc installations, broad surveys assessing potential, and computer simulations have occurred. Most installations to date have employed solar in parallel with the heat pump, i.e., the heat pump is an auxiliary, and the intrinsic properties of the vapor cycle are not therein exploited. The relative few which have used solar as direct series input to the heat pump have perforce used current heat pumps, which are not designed to accept and efficiently utilize the elevated evaporator temperatures of solar-supplied input. That is, they either may not run at input temperatures above 283°K (50°F) or can be forced to run only by energy inefficient techniques. Consequently they do not at all realize the large COP increase available. Likewise, the surveys and computer studies have considered heat pumps having current performance characteristics, i.e., max. COP's of 3 to 3.5, and not the potential of machines designed for the solar task, nor have they seriously considered the opportunity to utilize inexpensive collectors or storage advantages (such as ground-coupling) that exist for the series configuration. Reference 1 discusses these situations in detail.

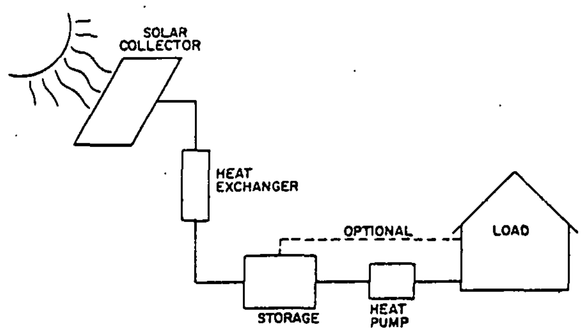

Fig. 3. Schematic of Solar Assisted Heat Pump System.

A basic Solar Assisted Heat Pump (SAHP) configuration is shown in Fig. 3. Solar collectors supply thermal storage, typically a large water tank, which is the heat source for the heat pump. A mode for bypassing the heat pump for direct solar heating can be included for those periods when the solar-supplied temperature is high enough. The collectors may be either liquid or air-cooled and can have a relatively high loss coefficient, since the collector-temperatures will not be greatly above ambient. Air-cooled collectors probably have the greater potential for low cost, and e.g., could be used with an air/water heat exchanger near them, and indoors, to allow hydronic piping to storage.

Such a SAHP could provide heating and cooling for single family residential, multi-family, and commercial buildings up to loads of approximately 25 tons, It thus can serve the same applications as current air-to-air heat pumps, but with substantially higher COP's, and expanded geographic range. Moreover, since the source temperature can always be kept sufficiently above freezing (and would probably be liquid in most systems), there is no need for a defrost cycle, a necessary feature in current air-source heat pumps which has traditionally been a source of energy inefficiency and reliability problems due to cycling and extra load on the compressor. The liquid source would provide good heat exchange (small ΔT's) in the evaporator, and the water loop could be reversed in the cooling season to allow heat rejection to the storage tank, which can be cooled at night to provide a lower temperature sink than ambient. In certain areas the collectors can assist in this process. Thus, although solar does not assist in the cooling mode, the solar system components can. The indoor heat exchanger could also be of the liquid type for low ΔT, hydronic piping to coils, and the option to re-route water flow instead of refrigerant flow.

The strong potential of the SAHP can be realized only if suitable heat pump hardware is developed. Certain significant changes must be made, not simply small adjustments, but these are well within the technology and capability of current manufacturers - given the market incentive to apply them. These changes may imperatively produce a higher first cost of the machine, but the energy and life-cycle cost savings they can provide can justify this to buyers.

The key to the development problem is making the heat pump operate efficiently and reliably over the input temperature range, 277 to 311°K (40 to 100°F) wherein the attendant suction vapor densities and system mass flows are very high compared to present operating conditions. The positive displacement reciprocating compressors used in the size heat pumps of interest here have a constant displacement volume (bore x stroke x no. of cylinders) and, therefore, at a given (constant) speed, force a mass flow rate approximately proportional to the suction density through the system. The vapor density increases rapidly with suction temperature because of the attendant saturation pressure increase. The effects of this situation on a heat pump (not specifically designed to accommodate them) are many and complicated and can not be dealt with in any detail here. In brief, unduly high pressures and temperatures can develop at the compressor outlet, the condensor can become overloaded and choked up, the expansion valve may not pass the flow and thus starve the evaporator--giving excessive superheat, the balance between liquid and vapor phase may be incorrect, and the refrigerant may just "run around and hide" in various places since there is such a relatively large amount trying to circulate. Of special importance is potential damage to the compressor, particularly the valves, by the high pressure and temperature. And, of course, performance is not efficient.

Changes to accommodate the solar input must be energy efficient, e.g., not of the hot gas by-pass type, in order to realize COP and capacity advantages. An important first step is the use of suitably large and effective heat exchangers to allow the high heat loads to be handled at reasonable temperature splits. This step is vital to effective use of the solar input. Additionally, sufficiently large expansion valves should be used. Externally equalized thermostatic expansion valves appear to offer the best pressure-drop-mass flow characteristics, and the bulb charge selection offers flexibility, including the possibility of newly developed charges if necessary. Multiple valves or an auxiliary by-pass might be employed. Most importantly, however, is the compressor and its ability to modulate the system. Some form of capacity control appears tantamount to success. A salient first choice is variable speed, not a new technique at all. But primarily it has been used to allow operation over a wide range of suction temperatures toward the low side. In a SAHP it can be used to extend the range of efficient suction temperatures toward the high side, with the low speed used for the cooling mode and the low end of the heating mode. A continuously variable speed would be desirable from a theoretical point of view, but in practice a 2/4 pole or 4/8 pole motor producing a discrete step in capacity would probably be satisfactory, with the lower speeds preferred. Alternatively compressor capacity modulation could be provided by cylinder unloading or the use of dual compressors. These methods, too, have previously been employed in VC machinery, and like the two-speed motor produce a step in capacity. The suction temperature at which the step occurs must be optimized as a function of climate, collector size, etc.

In order for SAHP performance to lie within the projected band of Fig. 2, the isentropic efficiency must remain high as suction temperature increases, which is contrary to the usual trend. The use of slow compressor speeds, high bore/stroke ratio cylinders, and efficient valve designs can serve to accomplish this. These three factors also promote high volumetric efficiencies, which tend to increase with suction temperature anyway, but can peak at high vapor densities. Thus, the variable speed method of capacity modulation also has these other important advantages.

It is important to note that as COP increases to high values and compressor work diminishes that the parasitic power requirements have a greater effect on COP and an effort to keep them down is important.

Relative to the incentive of the potential high COP's available at high temperatures as dictated by theory, which has existed for many years, is the question of how far up the COP curve it is truly practical to attempt to climb. This depends, inter alia, on the amount of time solar supplied storage is actually at the highest levels for a given collector type and area, storage volume, and climate. Indeed, the system must be optimized as a whole. There are many trade-offs of cost vs. performance to be addressed when incrementally climbing the COP curve, which include ensuring that performance in the medium high range, say 283 to 300°K (50 to 80°F) is not sacrificed by extending the range to the limit.

To implement the development of effective Solar Assisted Heat Pumps, the Solar R&D Branch for Heating and Cooling of the Department of Energy's Solar Division is supporting three two-year development programs which will result in prototype hardware. The contracts, awarded to successful respondents to an RFP, are with Lennox, Northrup, and General Electric (Schenectady, NY) and concist of three phases: (1) conceptual design and commercialization plan (2) detailed design and performance analysis and (3) fabrication and laboratory testing. Lennox is addressing 3-ton residential and 7½ to 10 ton multi-family/light commercial applications using a two-speed compressor with several different system configurations. General Electric is studying a range of sizes, applications, and types of systems and is developing a continuously variable speed compressor drive. Northrup, Inc., which unlike the others does not manufacture its own compressors, is working with several compressor manufacturers on a variety of systems. Dunham-Bush will supply them with R&D versions of a 25-ton rotary screw compressor, adapted to efficiently utilize solar input, and an innovative 3-ton reciprocating compressor which is the analog of a multiple (4)-slide rotary compressor in its ability to accept multiple level inputs and outputs and match compression ratio to operating conditions. This machine is two-speed, utilizes a "stepped" expansion, effective use of sub-cooling, and has projected performance which closely tracks the COP curves in Fig. 2. Northrup will also develop a 7½-10 ton machine using modified compressors from other suppliers. The objective of all three contracts is to produce a marketable heat pump which takes advantage of the high COP's available from solar energy in the 283°K (50°F) and up range, and which will represent the first generation of specifically solar-assisted heat pumps. In conjunction with the hardware programs, Singer is carrying out a comprehensive study for DOE to identify the most cost effective and marketable SAHP systems as a function of geographic area and economic climate.

Brookhaven National Laboratory provides support to DOE as technical monitor of these solar heat pump projects and additionally is carrying out an in-house program to develop SAHP technology. This work includes the construction and operation of a SAHP simulator and laboratory model heat pump to conduct laboratory tests of SAHP performance, including evaluation of the hardware developed by the contractors. A current series of tests is investigating attainable COP's as a function of evaporator and condenser temperature, compressor capacity control technique--particularly variable speed, refrigerant, heat exchanger size, and expansion valve configuration for both steady state and transient operation. In addition to parametric type of testing, the simulator will be able to carry out computer controlled simulations of complete solar system operation for appropriate weather and load scenarios.

4. RANKINE/VAPOR COMPRESSION SYSTEMS

These systems are characterized by the high cost, principally the collectors, of the Rankine power portion but offer promise in cooling COP performance if high cycle temperatures and effective condenser heat rejection can be utilized. Because of the trends in cost/ton and sophistication of hardware, they appear to be only suited for sizes 15 to 20 tons and up in the near term and not for single family residential use. Incorporating a heating mode can improve cost effectiveness. Ref. [2] gives a review of solar Rankine technology and Ref. [3] treats costs.

The VC portion of the system is thermodynamically conventional, but in one generic version utilizes a centrifugal compressor, driven on a common shaft by a high speed turbine, and a low density, high performance refrigerant, such as R-11 or R-113. UTRC is developing an 18 ton turbocompressor heat pump of this type using R-11 in both loops and a power loop max. temperature of 417°K (290°F). Carrier is developing a 25-ton chiller with the same max. temperature and integrated electric motor. GE, Airesearch, and Honeywell have been developing turbocompressor units of various sizes at 367°K (200°F) input under the "404" Program.

Another type of Solar Rankine system uses the fossil-fired superheat of steam vaporized by solar to give power cycle temperatures to 811°K (1000°F). These systems require small, efficient steam turbines which have good off-design performance so that solar-supplied superheat can also be used in the future. Energy Technology, Inc. and Univ. of Pennsylvania are developing 20-ton systems of this type.

All of these projects are DOE supported and BNL is technical monitor for all but the "404" Program.

5. SUMMARY

The Solar Assisted Heat Pump offers significant performance and economic potential and should receive serious development attention to investigate whether it can be realized. This work has begun under a structured plan of DOE supported R&D. Solar Rankine/VC systems can have viable application in the future in specific tasks if development is tailored properly.

6. REFERENCES

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