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A CHEMICALLY-ASSISTED MECHANICAL REFRIGERATION SYSTEM

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ABSTRACT

This paper introduces a new chemically-assisted mechanical refrigeration system that combines the advantages of the vapor compression, vapor absorption, and refrigeration/solvent resorption systems. Principles of the new system are presented and the search for suitable refrigerant/solvent pairs for the system is discussed. The feasibility of the proposed system has been verified by a sample calculation, which shows that substituting the system for the conventional vapor compression system, in some cases, will increase COP by 26%, and decrease compression ratio by 39%.

INTRODUCTION

Since the conventional vapor compression and vapor absorption systems follow the Carnot cycle, the phase changes inside the condenser and the evaporator are at constant temperatures if ignoring pressure drop through each exchanger. However, it often happens that the heat source and/or heat sink are undergoing temperature changes. Using the Carnot cycle in those circumstances would bring about a significant loss in the coefficient of performance (COP), and the bigger the temperature changes, the more the loss.

In order for the temperature of the refrigerant to match the temperature profiles of the fluids external to the refrigerant circuit, various efforts have been made. Altenkirch proposed an absorption-resorption system [1]. The part of the system, consisting of a generator and an absorber, the absorption loop, is identical to that of the absorption system. However, the evaporator and the condenser are replaced by a desorber and a resorber in a resorption loop. Instead of evaporating in a evaporator at a constant temperature, the refrigerant vapor is desorbed from the rich solution in the desorber with temperature increasing, which is caused by the fact that due to the heat input, only the component with a lower boiling point in the solution, the refrigerant, is evaporated. Therefore, the solution becomes poorer and poorer, at the same time the temperature of the solution has to rise, because the poor solution has a higher boiling point than the rich one. Analogously, the poor solution in the resorber absorbs the refrigerant vapor at decreasing temperature. During resorption and desorption the saturation temperatures at constant pressure depend on the concentration of the refrigerant in the solution.

Osenbruck proposed to substitute the absorption loop in the resorption system with a compressor [1]. Perhaps Vobach [2] is the latest to study the compression-resorption system. He gave this system the name of Chemically-Assisted Mechanical (CAM) refrigeration system.

THE PROPOSED CHEMICALLY-ASSISTED MECHANICAL REFRIGERATION SYSTEM

Figure 1 a) is a schematic of the proposed CAM system. It consists of a condenser (resorber), an evaporator (desorber), an expansion valve, a compressor, a pump, and a triple heat exchanger. As shown on that figure, the saturated refrigerant vapor (point 1) from evaporator passes the heat exchanger and absorbs heat from the rich solution. Then the low pressure superheated vapor is compressed in the compressor. The high pressure vapor (point 3) enters the condenser in which it is mixed with and dissolved into the circulating poor solution (point 6) to form a rich solution (point 7). During this process, the heat of mixing is rejected to the coolant and the temperature of the solution falls over a range which is to be matched with the temperature rise of the coolant.

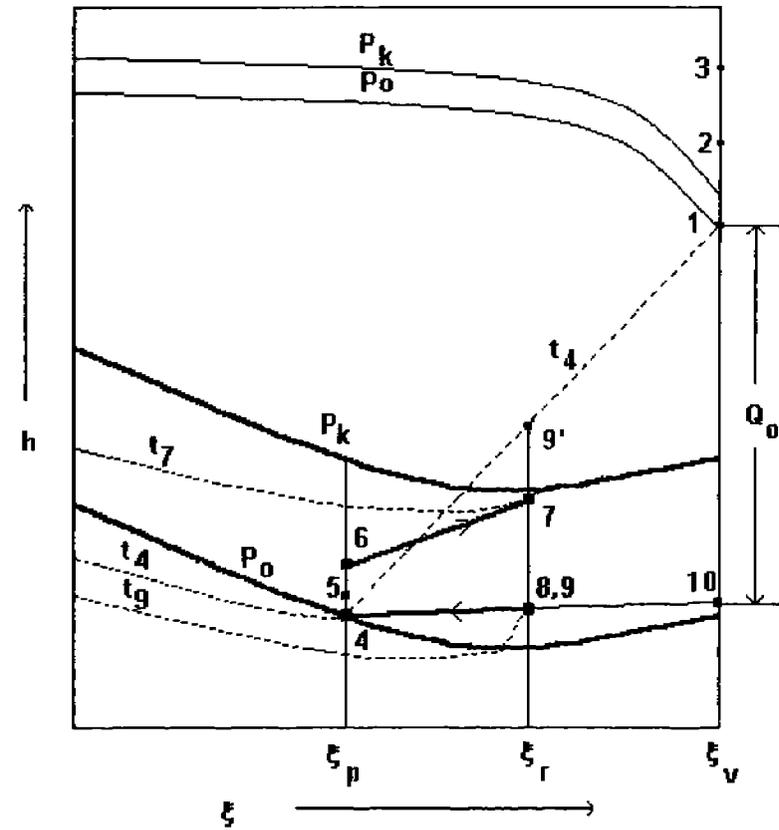
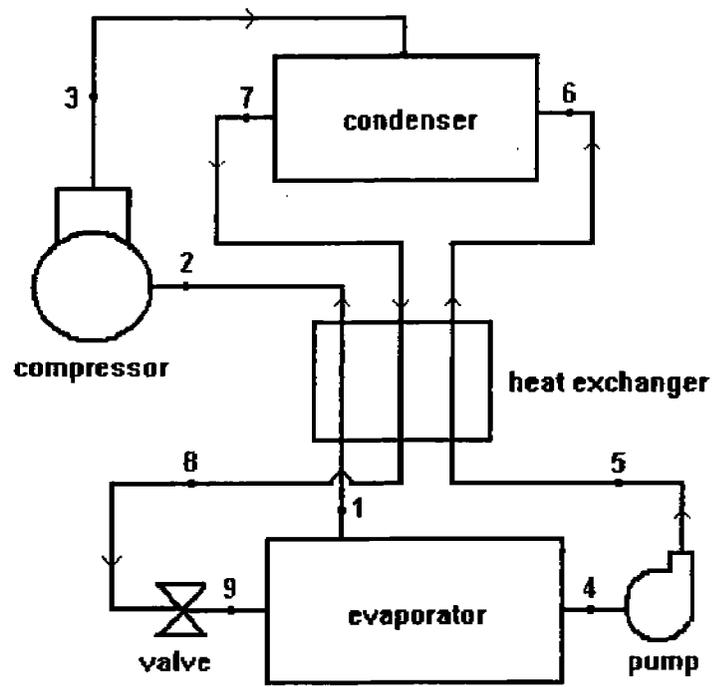


Figure 1. The Chemically-Assisted Mechanical Refrigeration System

With reference to Figure 1 a), the rich solution is subcooled in the heat exchanger by the vapor and the poor solution from the warm end of the evaporator. However, the subcooled load would be recovered at the cold end of the evaporator. This means that subcooling the rich solution in the CAM system not only increases refrigerating capacity, but also decreases the average boiling temperature.

Afterwards, the high pressure rich solution passes through the expansion valve that reduces the pressure to the low pressure existing in the evaporator. Then the rich solution goes into the evaporator where the solution boils and, with the increasing temperature, the refrigerant vapor evaporates from the solution gradually. During this process, the refrigerant absorbs both the latent heat of vaporization and the heat of dilution required to disassociate it from the solvent. The temperature profile is to be matched with that of the fluid being cooled. The vapor goes to the compressor through the exchanger. The poor solution is pumped through the heat exchanger back to the condenser.

The CAM cycle is depicted on an enthalpy-concentration (h - ξ) diagram as Figure 1 b). The rich solution, point 7, is located by high pressure, P_k , temperature t_7 , and concentration ξ_r . Process 7-8 represents subcooling of the rich solution in the heat exchanger. Since the adiabatic throttling is isoenthalpic, process 8-9 shrinks to a point on the diagram. However, because they stand on different pressure bases, point 8 is a subcooled high temperature liquid at P_k , while point 9 is a low temperature vapor-liquid mixture at P_0 .

Process 9-4 describes desorption in the evaporator. Point 9 stands for the rich solution in two phases at the inlet of the evaporator. If the vapor leaving the evaporator is in equilibrium with the poor solution, point 4, with concentration ξ_p , its state can be represented by point 1, situated at the intersection of the two phase isotherm t_4 and the dew point line at P_0 . Then the total enthalpy of the vapor and the poor solution at the outlet of the evaporator can be expressed by point 9'. As a result, the enthalpy difference between points 9' and 9 stands for the refrigeration capacity. The capacity based on the mass of vapor can be obtained by taking into account the similarity of the triangles 4,9,9' and 4,10,1. Q_0 is depicted on Figure 1 b). Process 5-6 represents heating of the poor solution in the heat exchanger. In the condenser the poor solution, represented by point 6, mixes with the refrigerant vapor, point 3, to form the rich solution, point 7.

It is known that the two pressures in the conventional compression or absorption refrigeration system are fixed by process requirement for the temperatures at which the condenser and the evaporator operate. In the proposed CAM system, on the contrary, pressures in the condenser and the evaporator can be adjusted by choosing different concentrations of refrigerant in the solution. As a consequence, where only one conventional cycle can be designed when the temperature profiles of heat source and heat sink are given, many CAM cycles can exist.

Compared with the vapor compression system, the major advantages of the CAM system are: matching temperature changes of the external source and sink to improve the overall thermal efficiency; lowering compression ratio to decrease discharge temperature of the compressor and the irreversible loss in the following mixing process; decreasing operating pressure to allow lighter, less expensive materials in the equipment; avoiding oil accumulation in the evaporator to maintain a high heat transfer coefficient; and providing a wetted surface for the condenser and the evaporator to enhance their heat transfer. Superior to the absorption system and the resorption system, the CAM system has a considerably high thermal efficiency if there is no waste heat available.

FEASIBILITY STUDY BY A SIMPLIFIED EXAMPLE

To investigate the feasibility of the proposition, a simplified CAM system without the triple heat exchanger was studied. Since data for the ammonia-water solution were available [3], it was selected for the sample calculation. It was assumed that the condensation temperature range is from 70 °F to 95 °F and, evaporation temperature range, -10 °F to 15 °F.

For a single stage vapor compression system, condensation pressure, P_k , and evaporation pressure, P_0 , are fixed by the corresponding temperatures, 95 °F and -10 °F. However, for the CAM system, P_k and P_0 can be chosen freely. For instance, P_k and P_0 were assumed 100 psia and 20 psia, respectively. Neglecting the subcooling of the liquid before the expansion valve, the fraction of ammonia in the saturated liquid, 100 psia and 70 °F, is 78.7% by weight. At exit of the evaporator, 20 psia and 15 °F, the fraction of ammonia liquid is 59.1% [3]. Because the vapor evolved from the evaporator in the CAM system is almost pure ammonia, the isentropic compression works for both systems were found with the help of the pure ammonia properties chart [3]. Then the specific refrigerating capacities for both systems were calculated by material and energy balance. Finally, the coefficients of performance (COP) were obtained, with neglecting the very small amount of work consumed by the solution pump in the CAM system.

The results of comparison between the ammonia compression system and the CAM system are shown in Table I. It can be seen that at the given operating conditions, substituting the CAM system for the single stage vapor compression system will increase COP by 26%, decrease compression ratio by 39%, and lower pressure level by nearly 50%.

Table I Comparison Between Ammonia Compression System and CAM Ammonia-Water System

	compression system	CAM system
P_k (psia)	195.8	100.
P_0 (psia)	23.7	20.
Compression ratio	8.3	5.
COP	3.49	4.39

SEARCH FOR SUITABLE REFRIGERANT/SOLVENT PAIRS

When selecting a refrigerant/solvent pair for the CAM system, besides the conventional factors, such as toxicity, flammability, chemical stability, corrosivity, and the danger to the ozone layer, characteristics of solution must be taken into account, from which the benefit of the CAM system would be obtained. The desirable refrigerant/solvent combination in the system should have high solubility in the condenser, but low solubility in the evaporator. Ideally one would like the solution to have a large negative deviation from the Raoult's law in the condenser and ideal solution behavior or even a positive deviation in the evaporator.

A temperature rise test is recommended as a preliminary screening test among many possible refrigerant/solvent pairs, because high solubility is marked by a substantial temperature rise when putting the refrigerant and the solvent together. For the prospective pairs, solubility tests need to be conducted first. Then functions of the liquid composition with different pressures and temperatures can be developed.

The relationship connecting vapor composition with the solubility data is the general coexistence equation that must be satisfied when phases coexist at equilibrium. Because the condensation and evaporation processes are nearly constant pressures in the CAM system, the Gibbs-Duhem equation, modified by Van Ness [5], is applicable. However, it proves difficult to integrate the equation at constant pressure. As a result, the constant temperature case is assumed for numerical integration, since it is always possible to repeat the constant temperature calculations at close enough temperature intervals to allow a constant pressure locus to be described.

By a series of simplifications and deductions, a mathematical model for calculating the vapor composition and the heat of mixing has been built, and a computer program has been developed. To verify the validity of this semi-theoretical model, a control sample was computed by the program. The integration procedure started from

the pure solvent to the pure refrigerant. The starting value of vapor composition for the refrigerant was estimated by the Raoult's law. The calculated results for the control sample were in good agreement with the experimental data [4].

CONCLUDING REMARKS

By absorbing both the positive and the negative experiences from previous work, principles of the chemically-assisted mechanical (CAM) refrigeration system have been completely understood. A new CAM system has been proposed. Since the key point for success of the CAM system is selection of a good refrigerant/solvent pair, thermodynamic analyses and numerical solution combined with experimental data have been proposed for the binary mixture.

A sample calculation revealed that under the circumstances of temperature-changing heat source and heat sink, the CAM system would demonstrate high superiority to other systems --- the high COP and low pressure level. It gives promise of replacing the conventional refrigeration systems.

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REFERENCES

1. Gosney W. B., Principles of Refrigeration, Cambridge University Press, 1982.
2. Vobach A. R., Development of a Chemically Assisted Mechanical Refrigeration Cycle, Final Report, U. S. Department of Energy, Oct. 1983, DE84-004962.
3. Bogart M., Ammonia Absorption Refrigeration in Industrial Processes, Gulf Publishing Company, 1981.
4. Zhang, C., A Proposed Research Program for a Chemically-Assisted Mechanical Refrigeration system, Final Report, Oklahoma State University, April, 1988.
5. Van Ness H. C. & M. M. Abbott, Classical Thermodynamics of Nonelectrolyte Solutions, McGraw-Hill, 1982.