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EXPERIMENTAL VERIFICATION OF A COMBINED POWER AND COOLING THERMODYNAMIC CYCLE

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ABSTRACT

A novel combined power-cooling thermodynamic cycle, for use with low-temperature, sensible heat sources, is under experimental investigation. In this power-cooling cycle, absorption condensation is used to regenerate the working fluid. This allows the expander exhaust temperature to drop significantly below the temperature at which absorption is taking place. This is an obvious departure from pure working fluid, Rankine cycle operation and is the source of cooling. Expander exhaust temperatures are controlled by the cycle parameters of expander exit pressure (absorption pressure), expander isentropic efficiency, and the vapor properties (temperature, pressure, and concentration) at expander inlet. Experiments have been performed that show the power-cooling concept to be valid by measuring the expander exit-absorber temperature difference and they highlight the direction for future work.

INTRODUCTION

The thermo-chemical compression system of absorption refrigeration cycles is used to create a heat-driven alternative to the mechanical vapor compression cycle. It has also been incorporated into a power cycle, and was initially studied by Maloney and Robertson [1]. The cycle uses a binary mixture of ammonia-water as the working fluid and absorption condensation to regenerate the working fluid. The use of an ammonia-water working fluid was also proposed for use in a power cycle by Kalina [2]. In these cycles, boiling takes place over a range of temperatures at constant pressure. This reduces heat transfer related losses by providing a better thermal match with sensible heat sources. Goswami [3,4] has proposed a power cycle that takes advantage of these boiling characteristics, and capitalizes on the possible vapor temperature drop across the expander when absorption condensation is employed. This creates a heat-driven cycle that can simultaneously produce power and cooling. Suggested heat sources include flat-plate solar collectors, geothermal, and waste heat resources.

In this combined power and cooling cycle, low temperature heat (60°- 100° C) is used to drive a thermodynamic cycle based around the properties of a binary working fluid, ammonia-water. Power is produced by expansion of a high pressure vapor through an expander and cooling comes from the sensible heating of the expander exhaust. Since the cycle is a combination of Rankine power production and absorption refrigeration cycles, absorption condensation is used to regenerate the working fluid. This allows the expander exhaust temperature to be significantly below the temperature at which absorption is taking place. This is an obvious departure from pure working fluid Rankine cycle operation, where the limiting expander exhaust temperature is the vapor condensation temperature, subcooling effects aside. Therefore, in the power-cooling cycle, it is possible to expand the vapor to sub-ambient temperatures, thus producing a low temperature stream that can be used for cooling.

This cycle has been the focus of previous theoretical and experimental investigations [5-7], however, experimental power and cooling production had not taken place. Recent investigations have been performed to experimentally show the potential for simultaneous outputs of mechanical work and sub-ambient cooling by pursuing the temperature drop possible across the expander. This paper details the experimental facility, factors affecting cooling production, and experimental measurements of the expander temperature drop.

NOMENCLATURE

p_{inlet}	=	Expander inlet pressure
p_{exit}	=	Expander exhaust pressure
x_{vr}	=	Rectified vapor ammonia mass fraction
$\eta_{expander}$	=	Expander isentropic efficiency

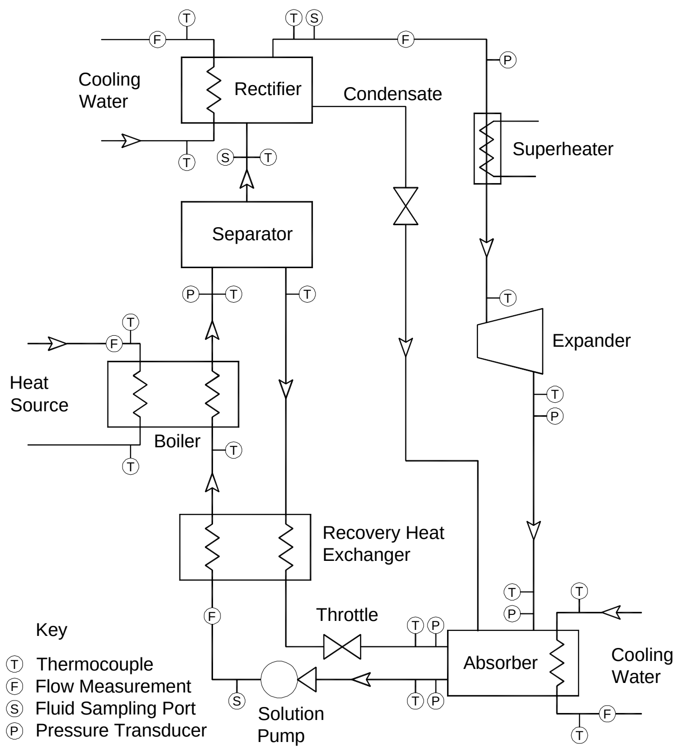

Fig. 1 Experimental power-cooling cycle schematic

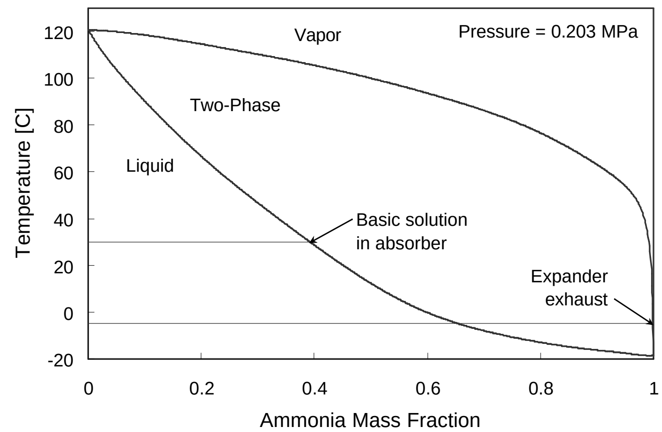

Fig. 2 Ammonia-water phase equilibrium diagram highlighting the source of cooling temperatures

CYCLE OPERATION

Figure 1 is the flow schematic for the experimental setup of the combined power and cooling cycle. Basic-concentration fluid is drawn from the absorber and pumped to high pressure via the solution pump. Before entering the boiler, the basic solution recovers heat from the returning weak solution in the recovery heat exchanger. In the boiler, the basic solution is partially boiled to produce a two-phase mixture; a liquid, which is relatively weak in ammonia, and a vapor with a high concentration of ammonia. This two-phase mixture is separated in the separator, and the weak liquid is throttled back to the absorber. The vapor's ammonia concentration is increased by cooling and condensate separation in the rectifier. Heat can be added in the superheater as the vapor proceeds to the expander. The expander extracts energy from the high-pressure vapor as it is throttled to the system low-pressure. To capitalize on any cooling available from the exhaust, an additional heat exchanger would follow the expander, however, this has not been implemented experimentally and is not shown in the figure. The vapor rejoins the weak liquid in the absorber where, with heat rejection, the basic solution is regenerated.

COOLING PRODUCTION

In the combined power and cooling cycle, the vapor temperature exiting the expander can be significantly below ambient conditions. Cooling can thus be obtained by sensibly heating the expander exhaust. The cooling aspect of the power-cooling cycle is due to the fact that the working fluid is a binary mixture, and at constant pressure the condensing temperature of an ammonia rich vapor can be below the saturation temperature for a lower concentration liquid. This is best illustrated with a binary mixture, phase equilibrium diagram, Fig. 2. The low concentration saturated liquid state represents the basic solution exiting the absorber, while the high concentration vapor is typical of the expander exhaust conditions. Note that this entire temperature difference may not be available in practical use due to the limited efficiencies of required heat exchange equipment.

According to the equilibrium diagram, Fig. 2, to maximize the difference between basic solution saturation temperature and vapor condensation temperature, the basic solution should be low in ammonia concentration and the vapor should be high. Also, partial condensation of the expander exhaust would cause an additional decrease in vapor temperature. This is typical since ammonia becomes saturated upon expansion.

To demonstrate the effect of expander inlet vapor conditions on exit temperatures, consider the entropy of the working fluid at the expander exit. Minimization of the exhaust temperature also implies a minimization of the vapor entropy at expander exhaust, assuming constant exit pressure. From this consideration an efficient expander is an obvious feature for low temperatures, but even an ideal device would only maintain the vapor entropy from inlet to exhaust. Therefore, expander inlet conditions should be considered. For a binary vapor mixture, entropy decreases with increasing pressure, increasing concentration, and decreasing temperature. The limit of these conditions, while still maintaining vapor, would be saturated, pure ammonia.

Figures 3 and 4 show the effects of inlet temperature, vapor composition, and expander efficiency on exhaust temperature. The intuitive effect of decreasing inlet temperature is shown in both figures. Figure 3 highlights the sensitivity to vapor composition, while Fig. 4 reiterates the benefit of good expander efficiency. The effect of exhaust pressure has not been shown, however, lower temperatures are expected with lower exhaust pressures.

EXPERIMENTAL SETUP

To investigate these effects, an experimental study of power and cooling production is underway. A boiling-absorption loop, used for previous work [7], has been modified and is used for this study. In the experimental setup, the boiler and recovery units are implemented with brazed, flat-plate heat exchangers. The rectifier is the combination of another flat-plate heat exchanger and a packed-bed entrainment separator. Absorption takes place in a pressure vessel equipped with

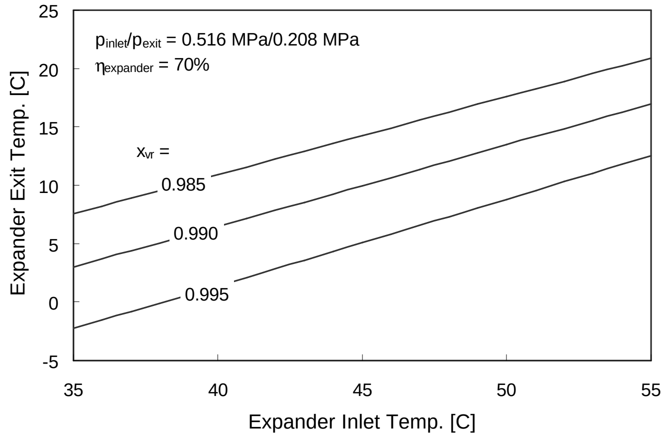

Fig. 3 Simulated effect of vapor concentration and expander inlet temperature on expander exhaust temperature

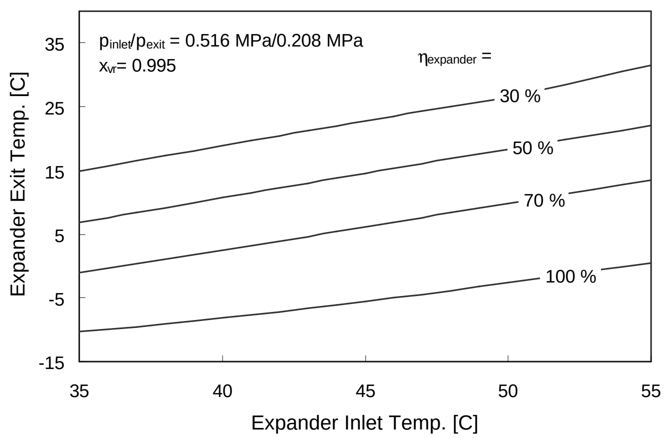

Fig. 4 Simulated effect of expander efficiency and expander inlet temperature on expander exhaust temperature

internal heat exchange coils. In the absorber, the vapor is bubbled into a pool of weak solution liquid through a perforated tube. Superheating is achieved by a variable-temperature heating tape that has been wrapped around a portion of the vapor plumbing. Heat for boiling comes in the form of hot water circulated by a separate system. This water is heated with resistance heating elements. Chilled water for heat rejection and rectification is produced with a separate water chiller.

The expander is a single-stage, partial admission turbine originally for use in an air-cycle cooling system. Its nozzles are sonic, i.e. they have a converging section only. Loading of the turbine is performed with a custom eddy-current brake connected directly to the turbine shaft.

Instrumentation is installed according to Fig. 1. A combination of manual recording and computer data acquisition are used for data collection. Liquid concentration measurements are obtained by analyzing a syringe sample with a gas chromatograph. Vapor measurements have been problematic with this method, so concentration is determined using thermodynamic property data, with an assumption of

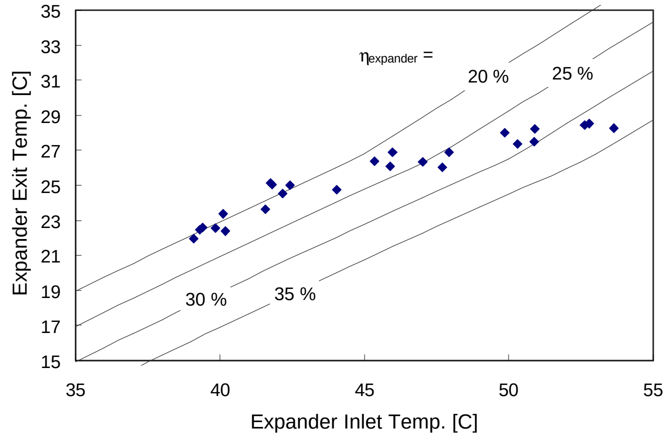

Fig. 5 Experimental data points and simulated performance data

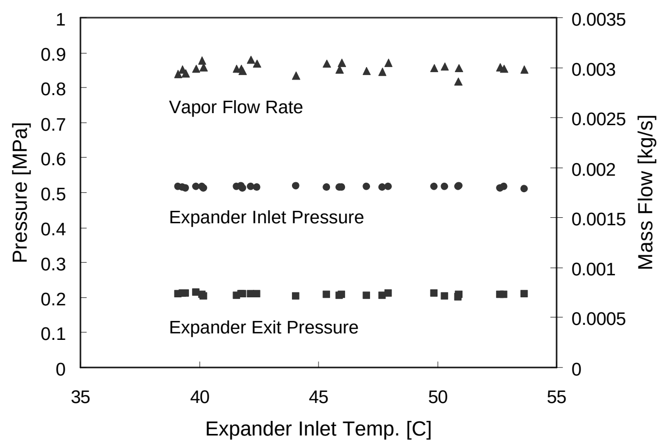

Fig. 6 Experimental expander-related parameter variation

saturated vapor at rectifier exit, and the measured temperature and pressure at this location.

As indicated in Fig. 1, the mechanical power generated by the expander is not directly measured. Parameters such as power output and expander efficiency are currently derived from thermodynamic property measurements at expander inlet and exhaust. Direct power output measurements have been attempted by measuring the reaction torque of the expander. However, due to its low output power and high rotational speed (approximately 40,000 rpm) the torque is correspondingly small and difficult to measure accurately. Thus far, these measurements have not been used.

EXPERIMENTAL RESULTS

Experiments have been performed to not only provide a demonstration of the temperature difference of Fig. 2, but also to explore the effects of the expander inlet conditions on exhaust temperature. Through successive stages of rectification and superheating, the data points of Fig. 5 were collected. A nominal vapor concentration of 99.3 % ammonia was maintained by controlling pressure and temperature at rectifier exit. Expander inlet temperature was then varied by adding heat in the superheater. All other parameters that could have an

Table 1 Average parameter values for the experimental testing

Expander Inlet Pressure:	0.516 MPa
Expander Exit Pressure:	0.208 MPa
Vapor Flow Rate:	0.00299 kg/s
Vapor Concentration:	0.993 kg/kg
Rectifier Inlet Temp.:	83.4° C
Rectifier Exit Temp.:	41.7° C
Absorber Temp.:	31.4° C

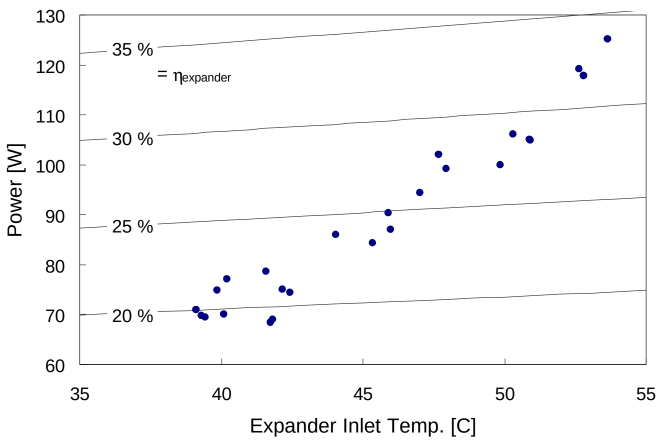

Fig. 7 Experimental expander power output based on measured thermodynamic properties and simulated performance data

effect on expander performance were held constant within the limits of the experimental setup. The variation of a few key parameters is presented in Fig. 6, and the average values of other system parameters are presented in Table 1.

The power and cooling cycle concept is demonstrated by the difference in temperature between the expander exhaust and the average temperature at which absorption is taking place. The average absorber temperature for all of the testing was 31.4° C. Clearly, all of the results in Fig. 5 fall below this temperature, providing a measurement of the temperature difference in Fig. 2.

Mechanical power was simultaneously produced during these experiments, and the values are presented in Fig. 7. All of the indicated shaft power was consumed in the eddy-current brake and dissipated as heat. The power values in Fig. 7 are based on the computed enthalpy change determined from the thermodynamic property measurements mentioned previously.

CONCLUSIONS

The power and cooling cycle concept has been verified by experimentally measuring the temperature difference possible between the absorber and expander exit. While the minimum temperature of 21.9° C in Fig. 5 is not sufficient to provide any practical cooling load, it does demonstrate the temperature difference of Fig. 2, which is the basis for the power and cooling concept.

A few conclusions regarding the implementation of the power-cooling cycle can be made. Referring to Figs. 3 and 4, high concentration vapor is needed to obtain reasonably low expander exhaust temperatures. This will likely necessitate the need for rectification if cooling is desired. Furthermore, the lowest exhaust temperatures are seen when the vapor is not superheated and enters the expander saturated. Therefore, the expander in this cycle should be a machine type that can efficiently expand saturated ammonia vapor and not be damaged by any condensed flow.

These results also show the possibility for improvement, however, the exact solution cannot be determined from these tests. The results of Fig. 5 indicate that the efficiency of the expander is low, and that lower exhaust temperatures could be expected with an improvement to its efficiency. Also, Figs. 5 and 7 indicate that the performance of the expander is sensitive to the inlet temperature of the vapor, i.e. the measurements deviate from the expected, simulated performance. Unfortunately, the measurements thus far are not sufficient to identify the source of inefficiency or the reason for these deviations. Further work is needed to separate the effects of: a true drop in expander efficiency due to saturated vapor conditions, excessive error in the temperature-based enthalpy measurements, or internal heat transfer that is obscuring true exhaust temperatures.

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