MINIATURE HEAT PUMPS FOR PORTABLE AND DISTRIBUTED SPACE CONDITIONING APPLICATIONS

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ABSTRACT

The Pacific Northwest National Laboratory (PNNL) is developing a miniature absorption heat pump for a range of microclimate control applications, including manportable cooling and distributed space conditioning. The miniature absorption heat pump will be sized to provide 350 W cooling, will have dimensions of 9 cm x 9 cm x 6 cm, and will weigh approximately 0.65 kg. Compared to a macroscale absorption heat pump, this represents reduction in volume by a factor of 60. A complete manportable cooling system including the heat pump, an air-cooled heat exchanger, batteries, and fuel is estimated to weigh between 4 and 5 kg, compared to the 10 kg weight of alternative systems. Size and weight reductions are obtained by developing a device that can simultaneously take advantage of the high heat and mass transfer rates attainable in microscale structures while being large enough to allow electric powered pumping.

INTRODUCTION

In a number of microclimate control applications, individuals must wear protective clothing which significantly reduces heat transfer from the body. Examples include workers exposed to hazardous materials, police wearing body armor, and military personnel exposed to nuclear, biological or chemical (NBC) warfare agents. The threat from NBC warfare agents on the modern battlefield imposes a substantial burden on U.S. military forces. Present and future individual protective equipment for military personnel includes a protective suit. While such uniforms provide protection against hazards, they significantly decrease an individual's military effectiveness. Personnel performing labor intensive tasks in a hot environment are susceptible to heat stress, especially when wearing protective clothing. The time that can be spent performing essential tasks, before succumbing to heat injury, is limited under these conditions.

Supplemental cooling will permit tasks to be performed under hazardous conditions in hot climates with enhanced efficiency and reduced heat stress. Although cooling systems can be integrated with protective suits, presently available systems are too heavy to carry for extended periods. Typically, a complete system sized for 8-hour operation with a cooling capacity of 350 W weighs more than 10 kg.

Based on research at PNNL, a compact absorption heat pump that can provide 350 W of cooling, and weighing approximately 0.65 kg, is technically feasible. When fuel, batteries, and an air-cooled heat exchanger are included, the complete system is projected to weigh between 4 and 5 kg, less than half the weight of a conventional microclimate control system.

The device will be primarily driven by thermal energy produced by the combustion of liquid hydrocarbon fuels. The energy storage density of liquid fuels exceeds the energy storage density attainable in conventional batteries by a factor of 130 (13,000 W_t/kg for liquid hydrocarbon fuel compared to 100 W_e/kg for batteries). An absorption cooling system still requires electric power to operate a liquid pump and fan, but its overall electric power requirements are approximately an order of magnitude lower than those of a conventional vapor compression system. The combination of reduced demand for electric power and the use of liquid fuels significantly reduces the weight of the primary energy source, compared to cooling schemes that require significant shaft work, such as vapor compression cycles.

In addition to manportable cooling, the miniature absorption heat pump can meet a number of important microclimate control and space conditioning requirements, including 1) vehicle space conditioning; 2) distributed cooling of buildings where the use of multiple small heat pumps eliminates the need for ducting systems, which typically waste 50% of the cooling produced by a central cooling system; 3) lightweight air-transportable space conditioning; and 4) autonomous cooling for shipping containers.

CONCEPT DESCRIPTION

Although the absorption and vapor compression cycles differ in the way compression is provided, both systems take the same approach to heat absorption and rejection. In both cycles, superheated refrigerant enters the condensing heat exchanger, where it undergoes constant-pressure heat rejection. The resulting condensate or mixture of condensate and vapor is then adiabatically expanded through either a throttling valve or a capillary. The mixture is then routed to an evaporating heat exchanger for constant-pressure heat absorption.

Compression is accomplished in the absorption heat pump system with a single-effect thermochemical compressor consisting of an absorber, a solution pump, a regenerative heat exchanger, and a desorber (gas generator). This is illustrated in Figure 1.

A conventional absorption heat pump relies on gravity to form falling films, which provide liquid to gas contact in the absorber and desorber. This approach has two decisive disadvantages for manportable microclimate control applications. First, the heat pump must be oriented so that the solution will fall over heat exchanger tubes and form a thin film. Deviations from the proper orientation will prevent the heat pump from working. Second, falling films have a film thickness on the order of 1 mm. This becomes a significant barrier to mass diffusion and results in a physically large absorber and desorber. As discussed below, the miniature absorption heat pump avoids both disadvantages by relying on the high rates of heat and mass transfer available in microstructures.

The miniature absorption heat pump depends on the extraordinarily high heat and mass transfer rates available in microstructures to radically reduce its size while maintaining cooling capacity and efficiency. Its performance ultimately depends on microstructure with individual features as small as 5 microns. The heat pump is a miniature device, but yet is sufficiently large to use a small but conventional solution pump.

A number of absorption cycles have been evaluated. Cycles can be classified based on the fluid combination and on cycle arrangements. The most widely used fluid combinations are lithium bromide (LiBr) and water, where water is the refrigerant; and water and ammonia (NH_3), where ammonia is the refrigerant. Cycle arrangements range from the single-effect cycle described above to progressively more efficient but complicated multiple effects. Previous research at PNNL simulated three absorption cycles; 1) single-effect $LiBr/H_2O$, double-effect $LiBr/H_2O$, and single-effect H_2O /NH_3.

The single-effect $LiBr/H_2O$ cycle requires a low pressure solution pump with a 41 kPa (6 psi) pressure rise, but the cycle is inefficient compared to the double-effect cycle. While more efficient, the double-effect $LiBr/H_2O$ cycle requires a higher pressure pump (410 kPa (60 psi) pressure rise) and is more complicated than the single-effect cycle. The pressure rise required for a H_2O/NH_3 solution pump (2400 kPa, 350 psi) is too high for currently available small pumps and results in a heavy and inefficient system.

Based on this screening, both the single-effect and the double-effect $LiBr/H_2O$ absorption cycles are candidates for cooling applications where weight and size are key issues.

HEAT PUMP COMPONENTS

An ongoing research effort at PNNL focuses on development of the components necessary for a miniature $LiBr/H_2O$ heat pump. All components of the single-effect absorption heat pump have been demonstrated. This section describes the miniature version of each component of a single-effect $LiBr/H_2O$ heat pump and presents a brief overview of the experimental performance results generated at PNNL. The prototype test articles for each component are illustrated in Figure 2.

- Desorber - Strong refrigerant solution enters the desorber and forms an ultra thin desorbing film. The ultra thin film (with a film thickness of approximately 100 microns) is maintained by a proprietary micromachined structure, which allows refrigerant vapor to evolve from the thin film. Thermal energy from a combustor can be used to heat the strong solution in the ultra thin film, evaporating the refrigerant vapor from the solution at a faster rate. The refrigerant vapor passes through the micromachined structure and is transferred to the condenser.

High heat transfer and mass transfer in the desorber results from the use of a mechanically constrained ultra thin film, which has a thickness approximately one-tenth that of a falling film. In theory, this should reduce refrigerant diffusion time in the thin film by a factor of 100. The use of a mechanically constrained thin film also means that the desorber performs regardless of its orientation. PNNL has developed and demonstrated the desorber. Preliminary results show that water is desorbed from the strong solution at a rate of 0.2 $g/cm^2/min$. This exceeds the performance of conventional desorbers by a factor of 10. We expect to significantly improve this level of performance.

- Condenser - The condenser consists of an array of microchannels with channel widths between 100 and 300 microns and channel depths up to 1 mm. The microchannel condenser has been demonstrated by PNNL. Heat transfer rates in excess of 30 W/cm^2 were attained with a small temperature difference and low-pressure drop.
- Evaporator - The evaporator also consists of an array of microchannels with channel widths between 100 and 300 microns and channel depths up to 1 mm. Extensive experimental investigations of microchannel evaporation have been published by PNNL (Cuta et al. 1996). Results show that convective heat transfer coefficients of 1.0 to 2.0 W/cm^2-K are readily attainable, and heat transfer rates up to 100 W/cm^2 can be obtained with a small temperature difference. These heat transfer coefficients and rates exceed those of conventional evaporators by a factor of 4 to 6. Pressure drop is typically less than 6 kPa (1 psi).
- Absorber - Weak refrigerant solution enters the absorber and forms an ultra thin absorbing film. As with the desorber, the ultra

thin film (approximately 100 microns) is maintained by a proprietary micromachined structure. Refrigerant vapor passes through the micromachined structure and is absorbed in the weak solution. The absorption process results in a high rate of heat generation, which is subsequently removed from the solution by a microchannel heat exchanger.

High absorber performance results from the use of the mechanically constrained ultra thin film, which has a film thickness approximately one-tenth that of a falling film. This reduces refrigerant diffusion time in the thin film by a factor of 100. In addition, mechanically constrained absorption means that the absorber performance is independent of its physical orientation.

PNNL has developed and demonstrated the absorber, and preliminary results show that ammonia could be absorbed in water at a rate that generates between 10 and 30 W/cm^2. This is an extraordinary absorption rate that exceeds the performance of conventional absorbers by more than a factor of 10, and we expect to improve this level of performance significantly.

- Regenerative Heat Exchanger - The regenerative heat exchanger consists of arrays of microchannels with channel widths between 100 and 300 microns and channel depths up to 1 mm. Extensive experimental investigations of single-phase microchannel heat transfer have been published by PNNL (Ravigururagan 1995). Convective heat transfer coefficients of 1.0 to 1.2 W/cm^2-K are attainable. These heat transfer coefficients exceed conventional regenerator performance by a factor of 3 to 6.
- Combustor - PNNL has demonstrated a microchannel combustor for the Department of Defense Advanced Research Projects Agency (DARPA). The microchannel combustor can produce thermal energy at a rate of at least 30 W_t/cm^2, with a thermal efficiency between 82 and 85% (Drost et al. 1996). We plan to use the microscale combustor as the heat source for the miniature absorption heat pump.
- Solution Pump - PNNL has qualified several small, commercially available pumps for application in miniature LiBr/H_2O systems. While significantly larger than needed, these pumps are adequate for a proof-of-principle demonstration of the miniature absorption heat pump.

HEAT PUMP PERFORMANCE

Based on the experimental data we have collected to date, a prototype manportable cooler has been defined. This section presents the predicted performance of a single-effect, LiBr/H_2O absorption heat pump sized to provide 350 W of cooling. The system includes a water-cooled condenser and absorber, a water heat source for the evaporator, and a microchannel combustor with exhaust gas at 250°C as the desorber heat source. In many applications, water cooling will be available (from the vehicle radiator for vehicle cooling and from a cooling tower for space conditioning). Other applications, such as manportable cooling, will require an air-cooled heat exchanger for ultimate heat rejection from the system.

Table 1 summarizes the weight and performance characteristics for two systems: one appropriate for manportable applications and the other designed for vehicle or space conditioning applications, where we assume a lower cooling water temperature [7°C (45°F)] as compared to [15°C (60°F)] and a lower heat rejection temperature [32°C (90°F)] in the condenser as compared to [46°C (115°F)]. As Table 1 shows, the two systems are nearly identical, with a total heat pump weight of approximately 650 g and a coefficient-of-performance (COP) of 0.68 for the manportable design and 0.71 for the space conditioning design. COP is the ratio of the amount of cooling provided divided by the thermal energy supplied to the desorber. For the manportable design, 1 W of heat provided by combusting fuel would provide 0.68 W of cooling.

TABLE 1. MINIATURE ABSORPTION CYCLE UNIT CHARACTERISTICS

	Component Weights (g)	
	Manportable Cooling	**Space Conditioning**
Component	**COP = 0.68**	**COP = 0.71**
Combustor	54	52
Desorber	186	177
Evaporator	35	35
Heat Exchanger	35	36
Condenser	37	36
Absorber	106	118
Pump	200	200
Total	***653***	***654***

These device characteristics are a compelling example of the advantage of devices in the miniature size range. The specific cooling (cooling per unit volume) of the miniature heat pump is higher than that of a conventional macroscopic absorption heat pump by a factor of 60 (1.25 W/cm^3 compared to 0.02 W/cm^3) for a macroscale device. The absorption heat pump also requires considerably less electric power than a vapor compression heat pump (10 W compared to 120 W). This will reduce the need for manportable power generation or batteries for powering microclimate control systems.

CONCLUSIONS

By taking advantage of the high rates of heat and mass transfer attainable in microstructures, PNNL developed a miniature absorption heat pump with a cooling capacity of 350 W that weighs only .65 kg. Compared to a macroscale absorption heat pump, this was achieved with a reduction in volume by a factor of 60. A complete manportable cooling system, including the heat pump, an air-cooled heat exchanger, batteries, and fuel, is estimated to weigh between 4 and 5 kg, compared to the 10 kg weight of alternative systems.

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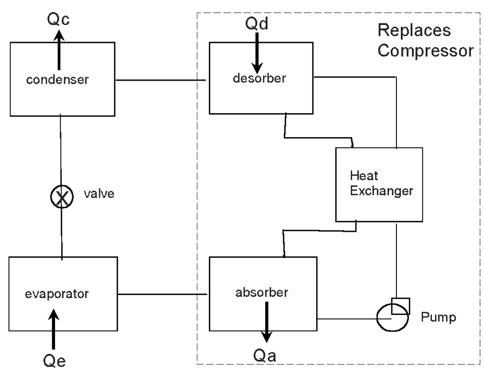

FIGURE 1 ABSORPTION SINGLE-EFFECT CHILLER

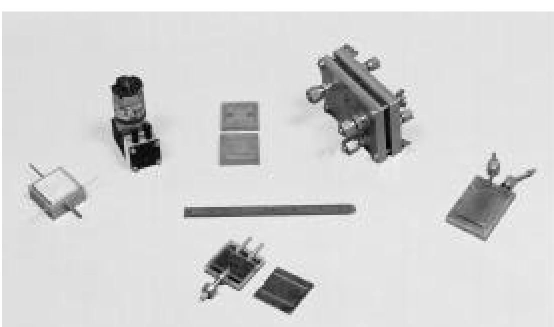

FIGURE 2 ABSORPTION HEAT PUMP COMPONENTS