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MINIATURIZATION OF AN AMMONIA-WATER ABSORPTION CYCLE HEAT PUMP USING MICROCHANNELS

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ABSTRACT

Small-scale, portable vapor compression cooling systems are encumbered with the need for electricity from batteries or a portable generator in order to operate the mechanical compressor. Heat actuated technologies, such as the absorption cycle heat pump, offer an alternative that can substantially reduce or eliminate the reliance on electricity. Heat can be provided by combusting high energy density liquid fuels or by recovering waste heat from other processes, such as fuel cell systems or vehicle exhaust.

With support from the U.S. Army, collaboration between the Pacific Northwest National Laboratory (PNNL) and Oregon State University (OSU) is endeavoring to develop miniaturized heat-actuated technologies for portable and personnel cooling. Progress on a miniaturized ammonia-water cycle is reported, including the recent operation of a 250 Watt breadboard system.

Microchannel technologies offer a unique approach for intensifying these transport processes by reducing the characteristic length-scale to less than a millimeter. In applying these techniques to miniaturize the absorption cycle heat pump, the major technical hurdles are associated with the absorber and desorber, because of the requirements for two-phase processing and for balancing heat and mass transfer. The PNNL approach for absorbers utilizes thin wicking materials within microchannels. OSU is developing desorbers using fractals that operate similar to a thermal inkjet printer. The principles of the concepts are presented along with experimental results from testing prototype devices operating with ammonia-water at conditions consistent with ammonia-water heat pump cycles. Potential for additional size and weight reductions is discussed. One application target calls for a 150 Watt portable cooling system for the individual soldier that weighs less than 6 pounds and more preferably less than 4 pounds.

Microchannels, Absorption Cycle, Heat Pump, Fractal, Wicking

INTRODUCTION

The lack of lightweight portable cooling is an issue for many military and civilian applications including for man portable cooling, vehicle cooling, tactical cooling and air portable cooling systems for air transportable structures. Furthermore, there is a lack of cooling technology for biological and chemical protection suites worn by first responders. Such technology would enable longer term (greater than four hours) operation in a "hot zone".

Conventional vapor compression cycle technologies rely on mechanical compressors to drive a cooling cycle, but these draw electrical power typically from the engine for vehicle cooling, from an auxiliary generator, or from batteries. Because of low energy density, typically in the range of 100-600 Whr/kg [1], batteries can dominate the weight of portable cooling systems. With hydrocarbon fuels having much higher energy densities, on the order of 10,000 Whr/kg, the ability to utilize heat to drive cooling cycles, such as through absorption cycle cooling [2], offers potential for smaller and lighter-weight cooling systems, as well as higher energy efficiency through the use of waste heat. In the past, heat actuated cooling concepts have not been attractive for portable applications primarily because of size and weight. Here, miniaturization of an ammonia-water absorption cycle heat pump through the use of microchannels is presented.

Process intensification—achieving high throughput per unit hardware mass—is made possible by microchannel architectures, which have been applied to many thermal and chemical unit operations, including heat exchange, reactions, and separations [3,4]. With these devices, thermal and chemical processing takes place through an array of channels having at least one dimension that can range from a few millimeters to just a fraction of a millimeter. Consequently, extremely rapid heat and mass transfer rates occur that allow for orders of magnitude reduction in hardware volume and mass.

Absorption cycle cooling involves two unit operations requiring gas-liquid processing, absorption and desorption, and processing gases and liquids together in microchannels presents unique challenges. Previous approaches have attempted to prevent intermixing of the phases by using planar porous contactor plates that are non-wetting for one of the phases, which then allows the two phases to flow along opposite sides while mass transfer occurs between the phases [5,6]. In a similar approach, two straight microchannels, each carrying one phase, are constructed to overlap slightly such that the interface between the phases is pinned at the gap [7].

New approaches are presented here for accomplishing desorption and absorption in microchannels. Desorption is accomplished using fractal structures as high flux heat sinks, while absorption is performed using thin wicking structures. These concepts are each described below followed by information on progress toward a 250-Watt-scale breadboard of a miniaturized absorption cycle cooling system.

FRACTAL DESORBER

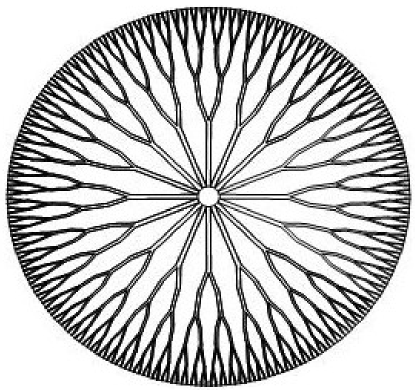

Figure 1 - Microscale fractal-like branching desorber

A desorber disk incorporating a microchannel, fractal-like branching channel flow network was developed for use in the ammonia absorption cycle breadboard. The fractal-like flow network employed is shown in Figure 1, and is quite similar to those employed in heat sinks that have been demonstrated to achieve high heat flux cooling while maintaining low pressure drops for single-phase flow [8-11]. The first demonstration of the fractal-like heat sinks used for ammonia desorption was reported in Cullion et al., [12]. In this latter study, energy was supplied by a thin-film Nichrome resistance heater vapor deposited on a silicon wafer.

For both the heat sink and desorber applications, the fluid is brought in normal to, and at the center of, the disk. Fluid then flows radially outward and is discharged at the periphery. In the desorber employed in the current study, sixteen channels emanate from the inlet plenum and each channel bifurcates 4 times into narrower channels, providing 256 channels at the periphery. The depth of the channel, by design, is constant and is approximately 150 µm, and the terminal channel width is 100 µm. Both values were limited by the technique employed to fabricate the disks; chemical etching of 304 stainless steel. The channel width and channel length ratios between consecutive branching levels are fixed. Based on recommendations by Pence [8] and Enfield and Pence [11], respectively, a length ratio of 1.4 and a width ratio of 0.7 are employed. The diameter of the disk is 38 mm and less than 1 mm thick.

Using the radial geometry shown in Figure 1, true symmetry can be achieved with an easily integrated exit plenum. There are several additional inherent advantages to employing the branching flow networks, particularly in the configuration shown in Figure 1. These include an increase in cross-sectional flow area following each branching level, which for single-phase flows greatly reduces the pressure drop compared to that through parallel microchannels. A pressure recovery occurs at the bifurcations, which serves to lower the total pressure drop in single-phase flows [10]. The presence and degree of pressure recovery depend upon the branching angle. In addition, symmetry at the inlet plenum is currently being shown, via high-speed-high-resolution imaging in Microscale Transport Enhancement Laboratory at Oregon State University, to possibly reduce flow maldistribution in two-phase flows, compared with that experienced in two-phase flows through parallel microchannel heat sinks.

Using a heat sink as a desorber, a binary mixture of water and ammonia is introduced into the center plenum of the heat sink, hereafter referred to as the desorber disk. Energy is added to the desorber disk in the breadboard using a series of miniature, impinging jets of high temperature air. Alternatively, a micro-combustor can be integrated into the device. For larger heat pump units, high temperature oil can be used to supply energy in a heat exchange desorber.

As energy is provided to the desorber disk, the ammonia water solution boils creating a liquid-vapor mixture exiting the disk periphery. In the annular shaped exit plenum, the high concentration ammonia stream is separated from the liquid stream, also known as the weak solution. Using mass flow meters capable of providing concentration measurements, coupled with temperature and pressure measurements in the exit stream, Cullion et al. [12] showed that the solution is in equilibrium in the exit plenum. Because the exiting vapor stream is in equilibrium with the exiting weak-ammonia liquid stream, as opposed to being in equilibrium with the incoming strong-ammonia liquid stream, this desorber disk is a co-flow desorber.

WICKING ABSORBER

The use of thin wicks for gas-liquid processing in microchannels has been successfully applied to phase separation [13,15], partial condensation with phase separation [14,15], and distillation. This patented technology [16] has also been demonstrated to work effectively in reduced-gravity on NASA's KC-135 zero gravity aircraft [14,15]. Here, thin-wick structures are used to accomplish ammonia absorption into solution for use in heat-actuated cooling systems.

The concept of a thin-wick absorber is illustrated by the schematic of Figure 2. A planar wick that is 0.1 to 0.5 mm

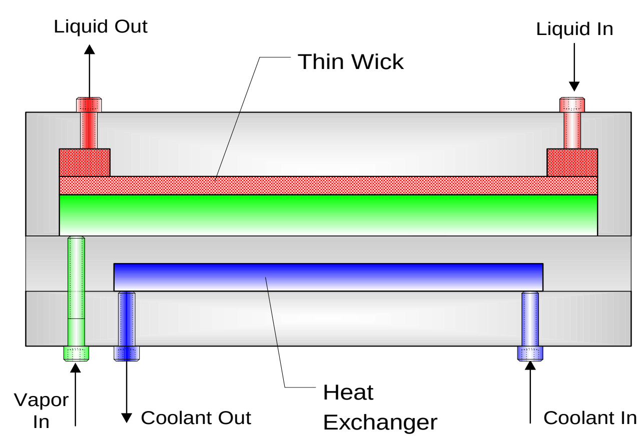

Figure 2 - Schematic of a Microwick Absorber

thick is located in a small channel with a plenum adjacent to the wick. Liquid flows through the wick from one end to the other by maintaining a pressure gradient along the wick. As long as the wick wets the liquid and the pressures at the liquid inlet and outlet are lower than the vapor plenum pressure, capillarity will cause the liquid to preferentially segregate into and flow through the wick, and vapor will flow preferentially through the adjacent plenum. As a consequence, mass transfer can occur between the vapor and liquid facilitating gas absorption. Because mass transfer resistance is dominated by the liquid phase, the thickness of the wick is the characteristic length-scale for mass transfer in the device.

One important advantage of this approach is the ability to recover from process upsets, because the low energy state of the solution is to reside in the wick. If phase crossover occurs—liquid into the vapor plenum or vapor into the wick—the system can be recovered by adjusting operating conditions. Furthermore, liquid flow is not gravity induced as it is in falling film absorbers, thereby enabling orientation independence.

A heat exchange channel is shown in Figure 2 adjacent to the vapor plenum but separated by a wall. Integrating heat exchange is necessary in order to remove the heat of absorption. Scale-up of the concept for a specified cooling load is accomplished by alternate stacking of the absorption channels and heat exchange channels, resulting in an interleaved structure that provides high heat and mass transfer area per unit hardware volume.

The wicking absorber concept was first investigated for ammonia absorption into solution using the test device shown in Figure 3, which accommodates a single wick 5 cm wide by 6 cm long located at the center of a 2 mm deep channel with vapor flow channels located on both sides, giving a total area for mass transfer of 60 cm^2. Vapor channel ports are located on top and on bottom of the device at both ends to facilitate both co-current and counter-current flow of vapor and liquid. Heat exchange channels are also built into the device adjacent to the vapor flow channels separated by a 0.76 mm stainless steel wall. A heat exchange fluid flows parallel to the vapor and liquid flow in either direction to enable co-current or counter-current heat exchange. Ports are included that allow three thermocouples to be inserted into the vapor flow channels on either side and adjustable to any point along the flow path. Typically, the thermocouples are located at the ends of the wick and approximately half way down the flow channel.

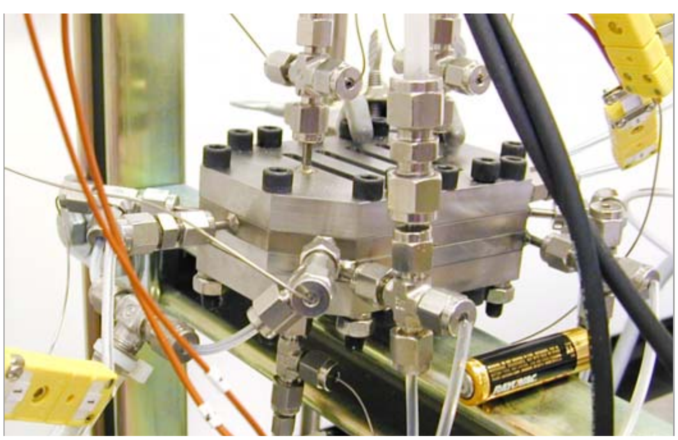

Figure 3. Single-wick test device.

The mass transfer performance of a wicking absorber is assessed using two dimensionless groups, an overall mean Sherwood number and a mass transfer Peclet number. The Sherwood number is calculated by

$$Sh_{om} = \frac{k_{om}\, h}{D_{AB}} \tag{1}$$

where h is the characteristic length-scale for mass transfer, D_{AB} is the binary diffusion coefficient, and k_{om} is the overall mean mass transfer coefficient, defined by

$$k_{om} = j \,/\, lmcd \tag{2}$$

where j is the average mass flux or total mass uptake divided by mass transfer area, and *lmcd* is the log-mean of the inlet and outlet concentration driving forces. Assuming mass transfer resistance is dominated by the liquid phase, *lmcd* is calculated assuming the liquid concentration at the gas-liquid interface is in equilibrium with ammonia vapor at a given temperature and pressure. The concentration driving force is the difference between the calculated equilibrium interface concentration and the bulk measured concentration.

The residence time of the solution is characterized by the inverse mass transfer Peclet number, calculated by

$$\frac{1}{Pe} = \frac{D_{AB}}{\bar{v}\, h} \tag{3}$$

where $\bar{v}$ is the average liquid velocity. The inverse Peclet number indicates the expected mass transfer effectiveness; 1/Pe<<1 indicates insufficient residence time for mass transfer, while equilibrium is approached as 1/Pe>>1. Approach to equilibrium can be expressed in terms of stream temperature as

$$\Delta T_{eq} = \bar{T} - T_{sat}\left(P_v, \bar{c}\right) \tag{4}$$

where $\bar{T}$ is the average solution temperature, and T_{sat} is the saturation temperature at a given vapor pressure P_v and average concentration $\bar{c}$. Close approach to equilibrium improves the performance of an absorption cycle heat pump by enabling lower solution recirculation ratios—the ratio of solution mass flow to refrigerant mass flow [2].

Equations 1 to 4 provide an assessment of mass transfer in an absorber device based on the assumption that mass transfer in the liquid phase dominates performance over heat transfer and vapor phase mass transfer. An overall mean Sherwood number that is greater than 2 would support the assumption, while an overall mean Sherwood number lower than 1 would indicate that productivity is being limited by some other effect with the potential for further process intensification. Furthermore, it is expected that the equilibrium would be approached as 1/Pe increases.

Proof-of-principle data were acquired using a 0.74 mm thick wick in the single-wick test device shown in Figure 3 and results are provided in Table 1 for a range of feed ammonia concentrations from 0 wt% NH_3 up to 26.4 wt%. For these tests, cooling water in the range of 28°C to 42°C was used to cool the absorber at a high enough flow rate to simulate isothermal operation by keeping the temperature increase of the water to less than 0.5°C. Calculated overall mean Sherwood numbers are substantially less than 1 indicating other transport processes are limiting performance. The equilibrium approach temperature ranged between 10°C and 40°C for 1/Pe in the

Table 1. Single-wick absorption results showing outlet ammonia concentrations and temperatures at given inlet concentrations and pressures.

c_{in} (wt%)	P_v (bar)	c_{out} (wt%)	T_{out} (°C)	1/Pe	Sh	ΔT_{eq} (°C)
0.0	1.38	15.6	67.5	1.6	0.58	39.5
14.4	1.68	25.7	51.8	1.6	0.59	24.8
21.1	1.57	25.7	50.1	0.9	0.60	14.4
21.0	1.61	24.8	52.4	1.0	0.46	12.7
21.0	1.62	25.3	51.6	1.3	0.52	11.8
26.4	1.58	30.1	40.9	0.9	0.55	9.6

vicinity of 1, showing a strong dependence on the starting concentration.

A prototypical air-cooled multi-channel wicking device for ammonia absorption is shown in Figure 4. This device contains three absorbing channels each containing two 0.30 mm thick wicks along the channel walls with a vapor channel in the center. Each wick has 50 cm^2 of area available for mass transfer. The absorption channels run right to left in Figure 4. Heat exchange for air cooling is provided by arrays of cross-current channels running into the page in Figure 4, with the dimensions of each channel being 1 mm wide by 3.1 mm high and 6.5 cm deep separated by 0.3 mm aluminum webs. Two rows of 60 channels are located between the absorption channels with only one row at the top and bottom of the stack. This provides for 625 cm^2 of primary and secondary heat transfer area for each absorption channel with a fin effectiveness of over 99%.

The device in Figure 4 was tested using ambient air at 20°C as well as with air heated to 49°C both at 150 SLPM flow. Results summarized in Figures 5 and 6 establish several key aspects. First, the ability to support compact absorption cycle cooling at the small-scale is demonstrated by ammonia absorption into 29 wt% solution at over 5 bar pressure with Sherwood numbers exceeding 1.0 and approach temperatures less than 10°C. Secondly, comparable performance was attained with two orientations of the device—the solution flowing downward in a vertical orientation and the solution flowing horizontally in the side orientation shown in Figure 4. Therefore, the prototype device not only enables the possibility

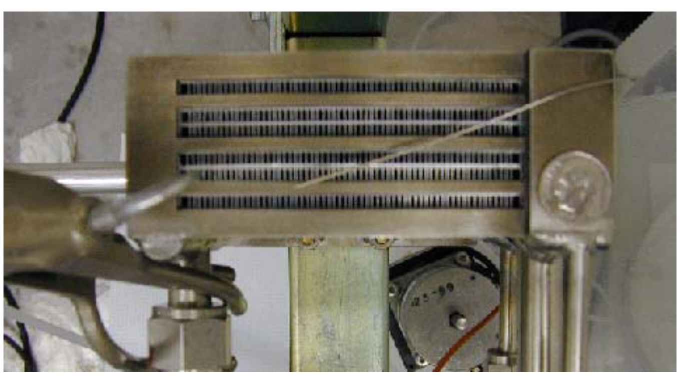

Figure 4. Looking down on a prototype three-channel Microwick absorber with a dime included for perspective.

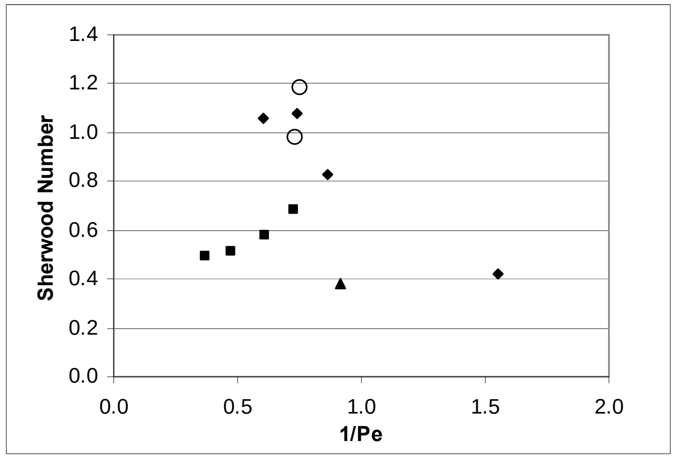

Figure 5. Mass transfer in the Microwick absorber pre-prototype represented as the overall mean Sherwood number as a function of 1/Pe with vertical flow at 1.3 bar, 10 wt% NH_3 feed and 21°C coolant air (◆); vertical flow at 1.6 bar, 22 wt% NH_3 feed, and 21°C coolant air (▲); side flow at 1.4 bar, 12 wt% NH_3 feed, and 50°C coolant air (■); and vertical flow at 5.4 bar, 29 wt% NH_3 feed, and 50°C coolant air (○).

of portable, compact cooling systems, but also orientation independence required for man-portable cooling. The mass flux of vapor into solution at 1/Pe=0.75 is 2 g/min which is corresponds to approximately 35 Watts of cooling.

MINIATURIZED HEAT PUMP SYSTEM

A breadboard system of a miniaturized absorption cycle cooling system is under development with a target cooling capacity of 250 Watts, which is typical of the heat generated by a single individual under moderate physical activity. This also

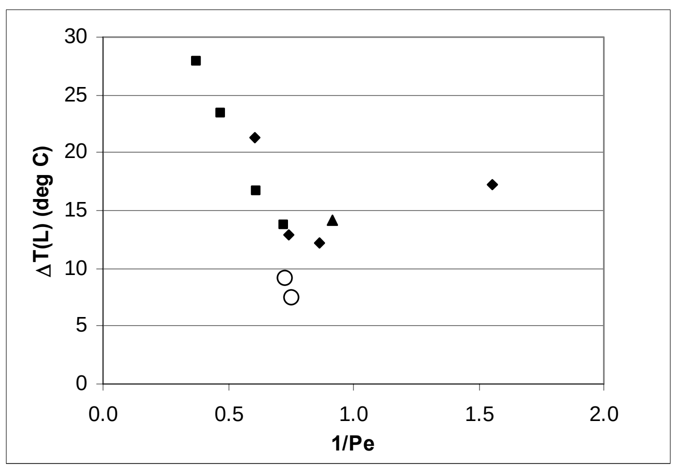

Figure 6. Approach to equilibrium represented as the solution outlet temperature minus the saturation temperature for ammonia absorption as a function of 1/Pe with vertical flow at 1.3 bar, 10 wt% NH_3 feed and 21°C coolant air (◆); vertical flow at 1.6 bar, 22 wt% NH_3 feed, and 21°C coolant air (▲); side flow at 1.4 bar, 12 wt% NH_3 feed, and 50°C coolant air (■); and vertical flow at 5.4 bar, 29 wt% NH_3 feed, and 50°C coolant air (○).

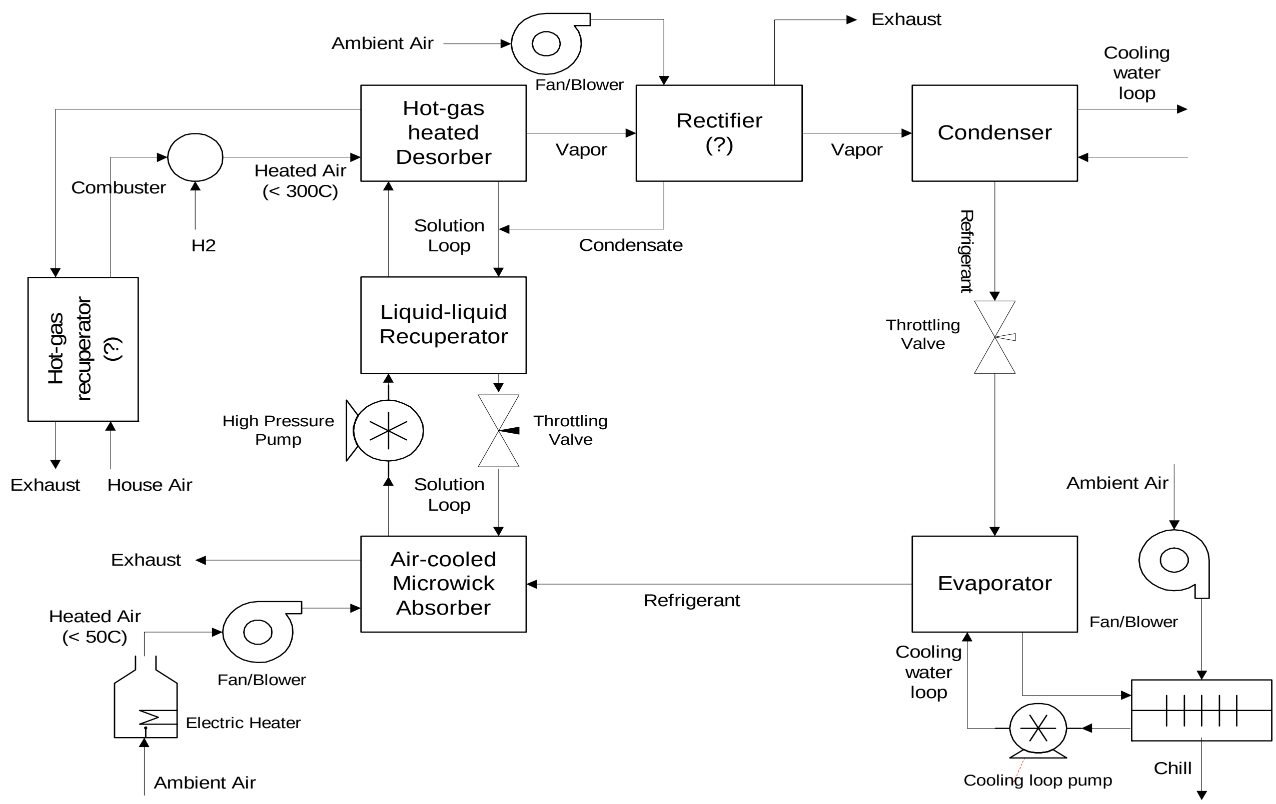

Figure 7. Process flow diagram for 250 Watt ammonia-water heat pump breadboard.

serves as an intermediate scale toward larger portable cooling applications for vehicle and habitat cooling. The key performance parameters and their target values are a reject temperature of 49°C; combustion gas for operating the desorber at 200-700°C; and providing cooling down to 10°C. The reject temperature represents the operating environment and 49°C (120°F) is typically used by the Army for evaluating cooling systems for hot field environments such as the Middle East.

The initial focus of the breadboard is validation of the absorber and desorber concepts in a fully operational heat pump system. A process flow diagram of the system is shown in Figure 7. Hydrogen is burned in air to provide a hot combustion gas stream at 200-700°C to the desorber. A microchannel air recuperator is included to recover heat remaining in the combustion gas exhaust stream, thereby reducing fuel consumption. Mass flow controllers are used to meter hydrogen from high pressure cylinders and air from the laboratory compressed air supply. The absorber and rectifier are cooled by air provided by low pressure fans, although initially the rectifier uses compressed air and a mass flow controller. Heaters are used on both air streams to preheat the coolant air temperature up to 50°C. The condenser is cooled with a water loop in the initial configuration of the breadboard, but this device will eventually be converted to an air-cooled device. A longer term objective is to cool the absorber, rectifier, and condenser from a single commercially available axial fan. The evaporator is heated from a closed-loop water loop that uses a commercial radiator and a fan for the cooling load. For personnel cooling, the evaporator water loop will supply chill to a cooling vest. For vehicle and habitat cooling, the evaporator coil will supply chill to recirculation air.

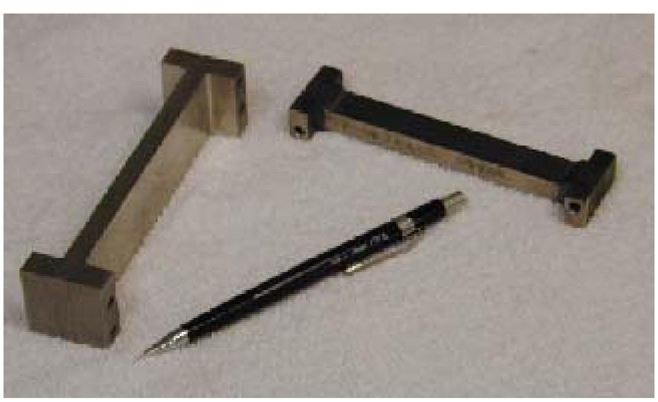

Figure 8. Evaporator (left) and solution recuperator (right) used in the 250 Watt ammonia-water breadboard.

The breadboard is configured with thermocouples, pressure transducers, and differential pressure transducers to monitor state points throughout the cycle, in order to facilitate comprehensive analysis of the system, including mass and energy balances around each component. Rotometers are installed to measure the flow rate of weak and strong solutions to and from the absorber. Samples are drawn from various points in the system, directed through an Anton Paar Model DMA4500 densitometer to measure ammonia concentration under pressure, and returned to the system to maintain inventories. Samples of the weak and strong absorber solutions can be drawn as well as samples of the rectifier condensate and weak solution from the desorber.

The evaporator, condenser, and solution recuperator are microchannel heat exchangers, two of which are shown in Figure 8. The evaporator weighs 257 g and has a heat duty of

250 Watts. The solution recuperator, a liquid-liquid heat exchanger with a specified duty of 514 Watts heat duty at 90% effectiveness, weighs 143 g, and will operate up to 30 bar pressure. Using the same design as Figure 4 above, two wicking absorbers, one with 12 and the other with 18 absorption channels, were built and installed in the breadboard, so that either one or both can be operated during a given test. Two desorbers have also been operated in the breadboard both heated by hot combustion gas from burning hydrogen. The first was a fractal desorber based on the concept described above. Alternatively, a microchannel device was also designed and fabricated to deliver the requisite heat to the incoming strong solution, and the subsequent gas-liquid mixture was separated down stream in a gravity separator vessel.

Initial open-loop testing of components and subsystems progressed to closed-loop testing of the entire miniaturized cooling system. Calculated cooling duties for closed-loop testing has steadily increased to a maximum level of 190 Watts, as determined from the flow rate and temperature change in the water flowing through the evaporator. At this condition, the heat delivered to the desorber was 500 Watts from 500°C combustion gas giving a COP of 0.39. The LHV of the fuel consumed was 700 Watts, yielding a COP of 0.28 based on fuel energy content. The evaporator operated at 13°C and heat rejection from the absorber and rectifier was to 48°C and 49°C air, respectively. Only the 18-channel absorber was used to accomplish a solution concentration change from 33.3 to 40.4 wt% NH_3 from the inlet to the outlet at an operating pressure 6.8 bar. At a liquid outlet temperature of 50.5°C, the approach to equilibrium in the absorber was 16.1°C, while the overall mean Sherwood number was calculated as 0.36 at 1/Pe equal to 2.6. The calculated absorber heat duty was 210 Watts, increasing 1050 L/min of 48°C cooling air to 59°C.

With the vapor and liquid flowing co-currently in the desorber, vapor was produced at 127°C and 19 bar of pressure. The rectifier cooled the vapor to 75°C to increase the saturated vapor ammonia concentration to 99.6%. The refrigerant flow rate was not measured directly and could not be accurately determined by mass balance. The heat duty of the recuperator was calculated as 745 Watts at 92% effectiveness.

The high pressure side of the cycle was at only 19 bar in the preceding example, which is made possible by the cold water used for cooling the condenser. A more reasonable high side pressure is 25 bar, which would facilitate heat rejection to a higher temperature from the condenser.

A second result reflects performance to date at the higher operating pressure of 24.6 bar, where 135 Watts of cooling was achieved as determined from the temperature rise in the evaporator water stream. At this condition, the COP was calculated as 0.25 based on the desorber heat duty and 0.18 based on fuel value. Again, only the 18-channel absorber was used to affect a solution concentration change from 31.0 wt% to 39.5 wt% NH_3. The approach to equilibrium in the absorber was 14°C at a 1/Pe of 2.4 with a Sherwood number of 0.51.

One of the difficulties so far in operating the breadboard has been obtaining adequate solution flow, which has been at only about 60-70% of the design rate. Increasing solution flow rate, as well as continuing refinement and optimization of operating conditions is expected to result in better than design performance. Efforts are also ongoing on improving the accuracy and sufficiency of measurements to improve performance analysis. Finally, next generation component development is anticipated to continue performance improvements and further process intensification of this system.

CONCLUSIONS

The foundation of an emerging technology for miniaturized heat-actuated cooling is established with demonstrated concepts for microchannel absorbers and desorbers, the two components in absorption chillers that require combined gas-liquid processing. A novel desorber technology has been created based on branching fractal structures that serve as compact, high flux heat sinks. The novel concept proven for ammonia absorption utilizes thin-wicks to segregate liquid from vapor to facilitate mass transfer at a length-scale of a fraction of a millimeter. Techniques for interleaving heat exchange and absorption channels provide highly effective heat transfer for cooling. Ammonia absorption into solution was first demonstrated as proof-of-concept in a single-wick test device. Data generated were used to design an air-cooled multi-channel prototype that operated successfully at the 35 Watt cooling scale, enabling scale-up to 250 Watts for a breadboard system.

A breadboard system of an ammonia-water absorption chiller has been developed with a target to provide 250 Watts of cooling at 10°C with heat rejection to 49°C. The initial focus has been to demonstrate the absorber and desorber within a complete, closed-loop system, which has been accomplished. The system has produced up to 190 Watts of cooling at 13°C while rejecting heat to 48°C and with a COP of 0.39, albeit at a lower high side operating pressure than required. The system has also achieved 135 Watts of cooling at the requisite high side pressure of 25 bar. Ongoing work in improving the operation and analysis of the breadboard system will continue to improve performance.

Miniaturized cooling technology is relatively immature as an emerging technology and theory supports the potential for substantial further improvements, ultimately resulting in a 150-300 Watt portable cooling system for an individual that weighs as little 4 pounds.

ACKNOWLEDGMENTS

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