

AN ABSTRACT OF THE THESIS OF

Kurt Fackrell for the degree of Master of Science in Mechanical Engineering
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Title: Flow Boiling of Lithium Bromide-Water Solution in Microchannels, with Application to Desorption.

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Recent studies of flow boiling within microchannels have shown high heat fluxes, leading to successful design and testing of compact heat exchangers, cooling systems for electronics and other high efficiency, miniature components. An experimental study of flow boiling of a concentrated salt solution in microchannels is presented. Experiments examined flow in single, circular microchannels, with a length of 25 mm and diameters of 0.127 mm and 0.25 mm, and in arrays of five rectangular microchannels, each with a length of 8.5 mm and a hydraulic diameter of 0.133 mm. Inlet concentrations of lithium bromide were varied from 47% to 57% by mass, heat inputs from 2.2 to 7.0 W per channel, and flow rates from 0.60 to 0.80 g/min per channel. Single channel tests yielded as much as 0.05 g/min of water vapor for the conditions examined. If an array of channels could produce vapor at a similar rate, it

may be possible to apply microchannel flow boiling in a compact desorber or evaporator. Unequal flow distribution in the microchannel arrays limited testing to heat input rates too low to verify array desorption.

Infrared visualization of flow at the exit of the microchannel was performed to document solution exit condition based on flow rate, heat input rate, and lithium bromide concentration. Visualization identified four basic exit conditions: steady dripping at low heat input rates, unsteady dripping with occasional vapor at moderate heat input rates, continuous droplet spraying at high heat input rates and flow rates, and long period oscillation between unsteady dripping and droplet spraying at high heat input rates and low flow rates.

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Flow Boiling of Lithium Bromide-Water Solution in Microchannels,
with Application to Desorption.

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NOMENCLATURE

A	Surface area (m^2)
c_p	Specific Heat (J/kg K)
g	Gravitational acceleration (m/s^2)
H	Total enthalpy (J)
h	Specific enthalpy (J/kg)
k	Thermal conductivity (W/m K)
L	Channel length (m)
D	Channel diameter (mm)
$\dot{m}$	Mass flow rate (g/min)
P	Pressure (kPa)
$\dot{Q}$	Heat input rate (W)
$\dot{q}$	Mean heat flux (W/m^2)
T	Temperature ($^{\circ}\text{C}$)
x	Concentration (% LiBr by mass)

Greek Symbols

α	Convective heat transfer coefficient ($\text{W/m}^2 \cdot \text{K}$)
Γ	Film flow rate per unit width ($\text{kg/s} \cdot \text{m}$)
μ	Dynamic viscosity ($\text{N} \cdot \text{s/m}^2$)
ν	Kinematic viscosity (m^2/s)
ρ	Density (kg/m^3)

Dimensionless Numbers

Ja	Jakob number $((T_h - T_{\text{sat}}) \cdot c_p) / h_{\text{fg}}$
Pr	Prandtl number $(c_p \cdot \mu / k)$
Re	Reynolds number $(V \cdot L / \nu)$

Subscripts

diff	Numerical difference
fg	Evaporation
h	Heat source
in	Inlet conditions
ideal	Theoretically predicted
loss	Lost or unaccounted for
out	Outlet conditions
ref	Refrigerant (Water)
s	LiBr-water solution
sat	Saturation temperature

1. Introduction

While vapor-compression refrigeration devices have become standard equipment for household refrigeration and air-conditioning, vapor-absorption chillers have found application in several specialized areas. The vapor-absorption cycle is powered by heat input rather than by mechanical work, making the system well suited to plants which already produce waste heat, remote locations where electricity is unavailable, and portable systems where the low energy density in batteries makes an electrical system prohibitively large. The trade-off, however, is in increased complexity and size. The mechanical compressor which provides the required pressure increase in a vapor-compression cycle is replaced by a series of five components that utilizes the phase change of a binary mixture to produce that necessary increase in pressure. Most of the size and complexity issues encountered in this cycle involve the absorber and the desorber, the two components responsible for respectively combining and separating the two species in the binary mixture.

The standard method for separating the two working fluids in a vapor absorption cycle desorber, known as "falling film desorption," is usually implemented in one of two ways. The first method is an external falling film layer, with coiled metal tubing, heated from within by steam or combustion gases. The binary solution is sprayed from one or more nozzles onto the outer surface of the coiled tubes, producing a thin layer of solution for easy evaporation. The second method uses an internal falling film, where the binary solution is allowed to flow slowly down the inside walls of parallel, vertical tubes. These tubes are then heated from the outside by

any convenient means. As the solution boils, the vapor rises through the center of the tube and is collected at the top. The desorption rate of these systems are constrained by two convective heat transfer factors: low surface area and low heat transfer coefficient. Microchannels present a potential solution to the size difficulties in these two desorbers, by increasing both surface contact area and heat transfer coefficient. The small scale of microchannels allows for hundreds of individual flow paths for the solution, creating greater total surface area for heat transfer than exists in conventional scale systems. Also, as described by Tuckerman and Pease (1981), in laminar flows heat transfer coefficient increases with decreasing diameter. However, microchannels add significant complexity in design and manufacturing, and require greater pumping power than falling film desorbers. Therefore, a microchannel based desorber could drastically reduce the size of a large refrigeration cycle component, but at greater cost to manufacture and operate.

The present study experimentally examines microchannel desorption of solutions ranging from 47% to 57% lithium bromide by mass through measurements of desorption rates in a) single, circular microchannels with a length of 25 mm and diameters of 0.127 and 0.254 mm, flow rates from 0.60 to 0.80 g/min and heat input rates from 5.0 to 7.0 W; b) two arrays of five rectangular, parallel microchannels each with a length of 8.5 mm and hydraulic diameter of 0.133 mm, total flow rate of 7.0 g/min and heat input rates from 22.0 to 28.0 W; and through infrared visualization of the solution exit condition for a single, 25 mm long, 0.127 mm diameter microchannel, with the same flow rates and heat input rates as the single channel test described above.

2. Literature Review

The following review focuses on the background necessary for a microscale desorption system, and on the research that has been done in its component fields.

2.1 Refrigeration Basics

All refrigeration systems share four thermodynamic processes. These four steps take advantage of the relationship between pressure and temperature in a closed fluid system. First, a fluid is compressed, increasing its temperature to above ambient. Second, the excess heat is transferred into the environment, often condensing the fluid in the process. Third, the fluid is expanded, decreasing its temperature to below the local ambient. Fourth, the now cold fluid receives heat from the area that is to be cooled, usually vaporizing the fluid, before returning to the first process. The difference between vapor-compression and vapor-absorption refrigeration is in the compression step. Common vapor-compression refrigeration systems compress the working fluid using mechanical work, through either an electric or combustion powered compressor. This pressurizing process requires continuous compression of a gas, which is always mechanically inconvenient and requires large power inputs. Vapor-absorption systems, on the other hand, use a chemical process to aid in the compression of the refrigerant. By absorbing the working fluid into an incompressible liquid, negligible work is required to cause the necessary pressure increase. The vapor can then be removed from the high pressure solution with a heat addition process. This heat addition process, necessary to separate the refrigerant from the concentrated

solution, takes place within the desorber. Further details on refrigeration cycles are available in standard Thermodynamic Textbooks, such as Çengel and Boles (1998).

2.2 Lithium Bromide

Though most fluid combinations could theoretically function within a vapor-absorption refrigeration system, efficient operation requires several specific properties. As discussed in ASHRAE Fundamentals Handbook (1997), the prime consideration for a prospective working fluid is the chemical affinity. The vapor-absorption cycle requires separating, or desorbing, the more volatile solution component for use as a refrigerant, and recombining, or absorbing, the solution for compression. Therefore, the solubility should be such that it is feasible to absorb the refrigerant vapor into the concentrated solution with reasonable surface area and temperature, but still possible to desorb the refrigerant out of the solution after the chemical compression process. Other desirable characteristics for a working fluid include high chemical stability, high latent heat, low fluid viscosity, low toxicity, low material corrosion and low cost. LiBr-water and water-ammonia combinations, while not ideal, match these criteria best of any currently known solutions.

Lithium bromide is a highly soluble salt, able to form solutions with water at up to 60% salt by mass at room temperature and pressure. It is non-toxic, and has a high latent heat, but is corrosive, and can crystallize during intensive boiling. Detailed characteristics and properties of binary LiBr-water solutions were measured and compiled by McNeely (1979) for use in vapor-absorption cooling systems.

Due to the advantages in latent heat and low toxicity, research has been performed on ways to limit the component damage from corrosion. Dockus et al. (1962) were among the first to examine how lithium bromide interacted with metals, and tested several additives, such as lithium chromate, that somewhat decreased the system corrosion. These additives formed inert films along metal surfaces to limit direct exposure to the solution. However, the most promising of these additives, lithium chromate, is toxic, unstable, and unusable above 65 °C (Verma et al., 1999). Another study by Guiñan et al. (1994) focused on the specific corrosion response of several common engineering alloys to concentrated and heated LiBr-water solution. This test established that while aluminum and 304 stainless steel corrode at an unacceptable rate, 316 stainless steel and titanium could temporarily survive exposure under working conditions. Further, in a low oxygen environment these metals could survive nearly indefinitely.

2.3 Binary Flow Boiling

Flow boiling involves heating a moving liquid in a channel until some or all of the liquid becomes vapor. Much of the fluid behavior during flow boiling is well understood and well documented, but flow boiling gains significant complexity when the fluid involved is a mixture rather than a pure substance. Extensive tests by Bennet and Chen (1980), with ethylene glycol-water solution, and Jung, et al. (1989), with R22-R144 solution, have shown a lower than predicted heat transfer coefficient for mixtures. In both studies, the predicted value was calculated based on a linear interpolation between the properties of the two component fluids. One reason for this

discrepancy between predicted values and measured values, suggested by Gropp et al. (1983), and applied by Wadekar and Hills (2001) to flow boiling, is the concentration equilibrium. As a mixture evaporates, the more volatile component vaporizes at a higher rate, creating a concentration gradient at the heated surface. Thus the rate of boiling is constrained by the rate of diffusion, as the less volatile component must be replenished at the heated surface for continued boiling. Since the two-phase heat transfer coefficient is a direct function of the boiling rate, a decreased boiling rate leads to decreased heat transfer coefficient.

2.4 Microchannel Flow Boiling

In the last few years, experimental studies of flow boiling within microchannels have documented high heat transfer rates and unconventional boiling regimes. Experiments by Bowers and Mudawar, (1994) showed heat transfer rates as high as 250 W/cm^2 for R-113 flowing in an array of 0.510 mm channels. However, they observed that the pressure drop increased rapidly above 100 W/cm^2 to as high as 32 kPa. Zhang et al. (2002) tested smaller microscale arrays, with hydraulic diameters ranging from 0.025 to 0.060 mm, and focused on pressure and temperature characteristics. One of the persistent problems in microscale systems is accurate local temperature data. The scale of the channels is too small for conventional measurements. Zhang et al. (2002) measured temperature with embedded resistors, distributed along the length of the microchannel, which yielded consistent results but with high uncertainties.

Flow visualizations in single channels and channel arrays have produced conflicting results, with some tests showing conventional boiling regimes, and other tests indicating unexpected variations (Kandlikar, 2002). Steinke and Kandlikar (2003) reported that observed flow boiling in 0.207 mm parallel microchannels followed the same progression of regimes as found in conventional channels. However, they also detected flow reversal, when phase change occurs so rapidly in a microchannel that bubble growth forces the bulk flow backward to be redistributed among the other channels temporarily. Peles (2003), however, determined that the onset of boiling was rapid enough to merit an entirely new flow regime, called “rapid bubble growth.” Flow reversal was also observed by Li et al. (2003) in a system of two 0.0571 mm microchannels, causing large scale oscillation in pressure and flow rate due to flow interactions between the two channels. Further, Jeong et al. (2003) recorded what they termed “eruptive flow boiling,” and showed that much of the large pressure variations can be explained by the microchannel surface roughness. Nucleation tends to begin at pits and cavities in a wall surface. However, manufacturing techniques and materials required to study microchannel flows result in uncommonly smooth channel walls, making the onset of boiling sudden rather than gradual.

Flow visualizations with channel arrays have also shown large variations in flow and boiling characteristics between channels. Hestroni et al. (2003) observed boiling in some channels for 80% of the length, while nearby channels were entirely in single phase flow. One promising approach to two phase flow distribution has been studied by Kim et al. (2003). By inserting the inlet of the channel deeper into the

plenum, observed flow inequalities were decreased by as much as 300% compared to parallel channels with the entrance flush with the plenum wall. However, the recorded flow distribution incorporated a water and air mixture to create two phase flow rather than flow boiling.

2.5 Microscale Desorption

Previous work has been done to decrease the size of components in vapor-absorption chillers, but most has focused on theoretical models. Garimella (2000) proposed a design for a minichannel absorber for ammonia-water systems. This model incorporated a falling film of solution over an array of 1.59 mm diameter steel tubes flowing with coolant, arranged in 75 layers of 40 tubes each. The proposed device could allow for a significant size decrease in absorber systems, processing 570 g/min of ammonia vapor while occupying a space about 15 cm on a side and 50 cm tall. However it would require liquid coolant circulated through minichannels with a pressure drop of 23.5 kPa in addition to the minimal pressure requirement of a falling film absorber.

While requiring greater complexity, and additional research and testing, microchannels offer an attractive possibility in improving absorber/desorber technology, providing for high rates of desorption, yet occupying only a fraction of the area required for current systems due to their high surface area and heat transfer rates.

3. Materials and Methods

3.1 Material Considerations for Wetted Components

A critical consideration when working with aqueous lithium bromide is material compatibility. Heated LiBr-water solution is highly corrosive, degrading aluminum and most stainless steels at a remarkable rate. Also, with a boiling temperature at atmospheric pressures of approximately 150 °C, additives to reduce corrosion and use of polymer components are impractical. As few manufacturers provide data lithium bromide corrosion resistance, much of the materials used had to be tested for compatibility before designs could be finalized. Guñan et al. (1994) established that 316 stainless steel and titanium could temporarily withstand concentrated LiBr-water solution, and that proved to be true in these tests as well. Further, Inconel, a nickel alloy, performed fairly well in corrosion testing, but no metal can be considered immune to deterioration under the conditions required for desorption at atmospheric pressure. Consequently, many of the primary components used in testing were manufactured from high temperature plastics such as PEEK and Teflon, which can tolerate the high temperature, high corrosion environment. For the items that require high heat conductivity or rigidity, titanium, Inconel, or 316 stainless steel were used, depending on availability. However, all metal components had to be rinsed thoroughly with deionized water after every use, as the preliminary nature of the test made an oxygen free environment impractical. Also, as a high concentration salt solution, aqueous lithium bromide is electrically conductive. Therefore all

instruments, probes and components in contact with the solution needed to be electrically insulated. Thus ungrounded thermocouples and Kapton heaters were used, though grounded thermocouples would have had a faster response time, and metal heaters a higher possible operating temperature.

3.2 Instrumentation

Table 3.1 outlines the primary instruments used for this test. Flow was provided and regulated by a pair of syringe pumps (Kloehn model VeraPump 6). These pumps allowed for continuous flow at low flow rates and high accuracy, but with a brief disturbance every 30 minutes as the stroke finished and the pumps switched. A Coriolis flow meter (Micro Motion ELITE) was used to measure the fluid density and temperature for both test configurations, and the flow rate for the multi-channel tests. For low flow rates, the syringe pump supply rate had lower uncertainty than the mass flow meter, however the flow meter was still used to establish solution density. The flow meter was custom fitted by the manufacturer with Inconel tubing to protect against lithium bromide corrosion. Power for the Kapton electric resistance heaters (Minco) was provided by a programmable power supply (Tektronix PS2520G), which allowed for control in both the magnitude and timing of heat supplied.

All temperature measurements were made using 1.59 mm diameter J Type Iron-Constantan thermocouples with an Inconel sheath. Once again, the Inconel was necessary to avoid instrument corrosion, and the thermocouples were ungrounded to

isolate them electrically from the conductive solution. The thermocouples were calibrated in a constant temperature bath and related to a NIST traceable thermistor (Omega, model ON-403-PP E3).

Table 3.1: Instruments used in single channel desorption test, including range and uncertainty.

Component	Detail	Range	Uncertainty	Calibration
Syringe Pump	Kloehn VersaPump 6	0.1 - 188 ml/min	0.42% of reading	Manufacturer
Mass Flow Meter	Micro Motion ELITE CMF010N Coriolis Type	3 - 1800 g/min	0.058 g/min	7 g/min: Catch and weigh, 1 minute, 20 repetitions
		0 - 5000 kg/m ³	1 kg/m ³	Manufacturer
		-50 - 125 °C	1 °C	Manufacturer
Power Supply	Tektronix PS2520G	0 - 54 W	0.05 W	Manufacturer
Thermocouple	J-Type 1/16" Inconel Ungrounded	0 - 90 °C	0.25 °C	Variable Temperature Bath, NIST Traceable Thermistor
Pressure Transducer	Validyne DP 15	0 - 138 kPa 0 - 150 Hz	0.4 kPa	0 - 5 psi: Dwyer series 477 Digital Manometer
			0.3 kPa	5 - 20 psi: Dead Weight Calibrator
Infrared Visualization	CMC Electronics TVS 8500	-40°C - 900°C	2 °C	Manufacturer
Mass Balance	Sciencetech SA120	0 - 120 g	0.0001 g	Ultra Class 50 g Calibration Mass

The pressure measurements were made using an oil-filled capacitance pressure transducer (Validyne, model DP 15), calibrated with a digital manometer (Dwyer, series 477) at low pressures and a dead weight pressure calibrator at high pressures. The oil served to both decrease the response time and ensure that the LiBr solution did not corrode the instrument. Finally, all mass measurements were taken with an analytical mass balance (Sciencetech, model SA 120), calibrated to within one tenth of one milligram using a 50g ultra class calibration mass. LabVIEW[™] software

(National Instruments) was used both to control the instruments listed above, and record and process the collected data.

4. Data Analysis

Concentration of lithium bromide to water was related to density and temperature using

$$x = A + \frac{B}{T} + C\rho + \frac{D}{T^2} + E\rho^2 + F\frac{\rho}{T} + \frac{G}{T^3} + H\rho^3 + I\frac{\rho^2}{T} + J\frac{\rho}{T^2} \quad (1)$$

where coefficients A through J are shown in Table 4.1. This correlation was obtained by solving for concentration in the relationship proposed by Lee et al. (1990) for calculating LiBr-water solution density with a given concentration and temperature. This formula allowed for inlet concentration to be established based on inlet density and inlet temperature measured by the flowmeter.

Table 4.1: Values of coefficients used in Eq. 1

A	-348.273	F	5.467374
B	-34468.2	G	-3.47x10 ⁻⁸
C	0.678594	H	6.56x10 ⁻⁸
D	6.92x10 ⁻⁶	I	0.001658
E	-0.00036	J	-1492.87

Concentration at the exit was calculated by a global species mass balance on lithium bromide, based on the mass and concentration of the solution entering and the mass of the water refrigerant collected at the condenser exit.

$$\dot{m}_{in} x_{in} = (\dot{m}_{in} - \dot{m}_{ref}) x_{out} \quad (2)$$

This ratio is valid as long as the system can be considered steady state, and no lithium bromide exists in the condensed water vapor.

The enthalpy of the LiBr solution at both the entrance and exit was calculated using the fourth order correlation proposed by McNeely (1979) based on the measured inlet temperature and concentration, calculated exit concentration, and calculated saturation temperature of the solution at atmospheric pressure.

$$h_s = 2.326 \{ A + B(1.8T + 32) + C(1.8T + 32)^2 \} \quad (3)$$

with

$$A = -1015.07 + 79.538x - 2.358016x^2 + 0.03031583x^3$$

$$B = 4.68108 - 3.03776 \times 10^{-1}x + 8.44845 \times 10^{-3}x^2$$

$$-1.047721 \times 10^{-4}x^3 + 4.80097 \times 10^{-7}x^4$$

$$C = -4.9107 \times 10^{-3} + 3.83184 \times 10^{-4}x - 1.078963 \times 10^{-5}x^2$$

$$+1.3152 \times 10^{-7}x^3 - 5.897 \times 10^{-10}x^4$$

Finally, the equilibrium thermodynamic energy rate required to produce a given amount of water vapor was found using an energy balance

$$\dot{m}_{in,s} h_{in,s} + \dot{Q}_{ideal} = \dot{m}_{ref} h_{ref} + \dot{m}_{out,s} h_{out,s} \quad (4)$$

providing an estimate of how much heat would be required to produce a given amount of water vapor under ideal conditions.

5. Single Channel Desorption

5.1 Experiment Set-Up

The single channel microchannel system had several advantages for initial testing: commercially available channels in 316 stainless steel and titanium, low solution flow requirements, high degree of flow rate control, and simple fluid supply system using conventional fittings. Thus, accurate tests could be performed without great expense and with varying conditions. The high degree of control over system variables allowed for tests using three levels of heat input rate, inlet solution concentration and mass flow rate, and two levels of channel diameter.

Figure 5.1 illustrates the test set-up used for single channel desorption. The aqueous LiBr solution was supplied by dual syringe pumps that allowed for near continuous flow and high accuracy at low flow rates. The pumps withdrew solution from the stirred reservoir and supplied a constant volumetric flow rate to the system. At the rates specified for this test, each syringe stroke lasted approximately 30 minutes, causing a brief disruption as the flow switched from one pump to the other. Flow temperature and density were monitored through the Coriolis flow meter at the pump exit. Next, the fluid entered the preheater, a titanium chamber heated with an electric band heater. Once again, the titanium was chosen for its material compatibility, not its heat conductivity. The preheater heated the LiBr-water solution to near saturation to allow for smaller heat fluxes within the channel itself. Temperature was carefully monitored within the preheater to ensure that no premature

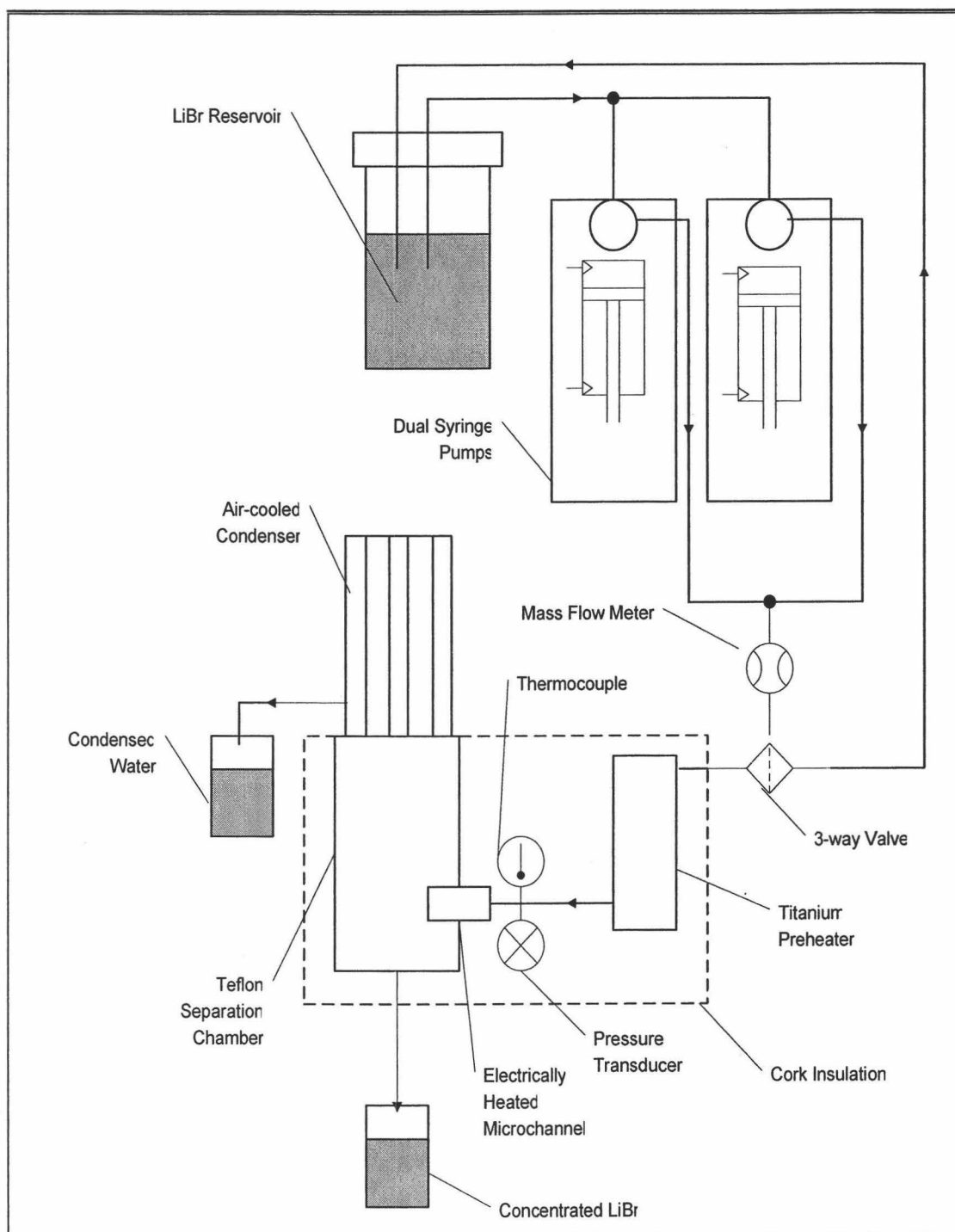


Figure 5.1: Schematic of test set-up for single channel desorption tests.

boiling occurred. Heated solution exited the preheater at its lowest point to ensure that any vapor or dissolved gases remained within the preheater rather than being transported with the flow of heated solution. Temperature and pressure were measured at the entrance to the microchannel to ensure that the solution was near boiling, but still below the saturation level.

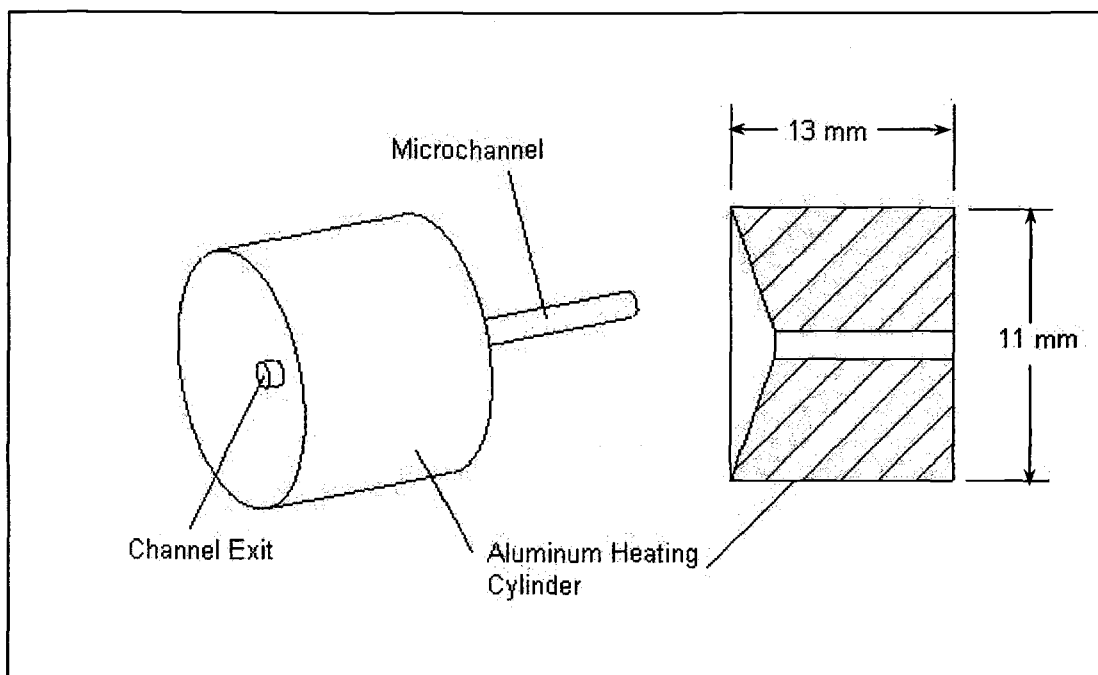


Figure 5.2: Single channel desorber and heating cylinder.

The channel itself, illustrated in Figure 5.2, was either a 2.5 cm long 316 stainless steel tube with an inner diameter of 125 μm , or a titanium tube of the same length and an internal diameter of 250 μm , depending on the specific test. Both tubes were chosen for their chemical resistance and commercial availability, and allowed for a comparison in characteristics based on tube diameter. An electrically heated aluminum cylinder fit snugly over the tube to provide the heat for the phase change.

The individual channels proved to be extremely susceptible to blockage due to particulate matter, such as dust, impurities in the LiBr-water solution, or corrosion. Thus the tubes needed to be replaced occasionally, and were stored in a deionized water bath between tests. After beginning phase change within the channel,

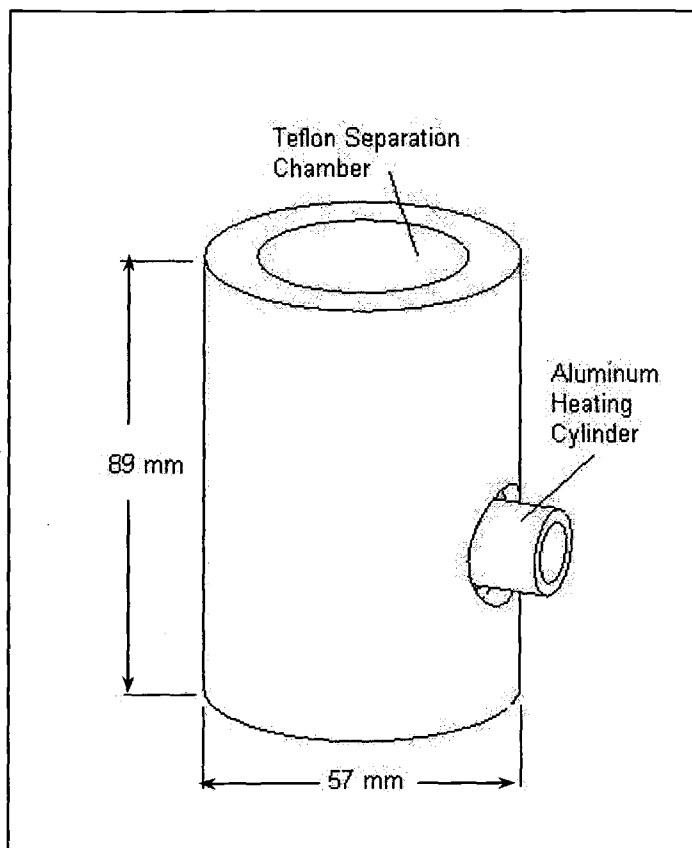


Figure 5.3: Separation chamber with heater.

the solution was expelled into a Teflon separation chamber,

shown in Figure 5.3, which allowed for gravity separation of the water vapor from the concentrated solution. The water vapor was condensed within an air-cooled condenser, then both the water and the concentrated solution were stored for examination. The entire heated portion of the test set-up was encased in rigid cork insulation to reduce heat losses. The peak temperature of the test set-up, about 150 °C, proved to be an awkward condition for insulation. Foam and polymer insulations cannot withstand the temperature required for phase change, yet high temperature ceramic insulations have a far lower insulative value. While cork is not the ideal

insulator either, it best matched the requirements for temperature limit, insulative properties (k value of 0.039 W/m·K) and machinability.

5.2 Procedure

The experimental procedure included the following steps: First, the syringe pumps were set to run continuously in a closed loop through the flowmeter then back to the reservoir to determine the reservoir concentration. Either deionized water or high concentration solution were added until the concentration required for the specific test was achieved. Next, the syringe pumps were programmed to supply the required flow rate of solution to the test loop based on the test case, solution density and solution temperature. The flow rates examined were chosen to characterize the range most likely to be useful for a compact, multichannel desorption system. Both the preheater and the channel heater were then set to the desired heating level until all temperature measurements reached steady state, and water vapor was gathering within the condenser. Tests were conducted in the following manner. When one of the syringe pumps began a new stroke concentrated solution and condensed liquid water were collected at the separation chamber exits for 20 minutes. This extended length of time accounted for minor variations in outlet flow and collected enough solution to decrease uncertainty in mass balance calculations. Temperature and pressure distributions were also recorded during the test period. The mass of the collected liquids was recorded, then a lithium bromide species mass balance was used to calculate the exit concentration based on the inlet flow rate provided by the pumps and the collected refrigerant. A conductivity meter was used to measure outlet

concentration, but the uncertainty level of $\pm 0.53\%$ LiBr by mass was too high for the data to be useful. The procedure steps were repeated as necessary to establish behavior under varying heat inputs rates, concentrations, flow rates and channel diameters.

5.3 Results and Discussion

Single channel tests were conducted with two channel diameters, three inlet concentrations, three power levels and three flow rates. While the four variables controlled had 54 unique combinations, a Taguchi design of experiments was used to

Table 5.1: Summary of single channel desorption results.

Test Conditions				Results		
$D(mm)$	$\dot{Q}(W)$	$\dot{m}_{in}(g/min)$	$x_{in}(\%)$	$x_{out}(\%)$	x_{diff}	$\dot{m}_{ref}(g/min)$
0.127	4.98	0.598	46.2	50.7	4.5	0.053
0.127	5.96	0.698	46.2	50.3	4.0	0.056
0.127	7.04	0.795	46.3	50.4	4.1	0.065
0.127	4.98	0.599	52.3	56.0	3.7	0.040
0.127	5.96	0.702	52.3	56.8	4.5	0.056
0.127	7.04	0.805	52.3	56.0	3.8	0.054
0.127	4.98	0.702	57.1	59.2	2.1	0.025
0.127	5.96	0.798	56.9	60.2	3.3	0.044
0.127	7.04	0.603	56.9	60.4	3.5	0.035
0.254	4.98	0.799	46.9	49.7	2.9	0.046
0.254	5.96	0.602	46.9	49.9	3.0	0.036
0.254	7.04	0.702	46.9	50.8	3.9	0.054
0.254	4.98	0.697	51.7	54.9	3.1	0.040
0.254	5.96	0.801	51.8	55.4	3.6	0.052
0.254	7.04	0.595	51.7	55.2	3.5	0.038
0.254	4.98	0.795	56.6	58.9	2.2	0.030
0.254	5.96	0.601	56.6	59.0	2.4	0.024
0.254	7.04	0.698	56.7	60.3	3.6	0.042
± 0.005	± 0.05	± 0.002	± 0.1	± 0.2	± 0.2	± 0.002

identify eighteen combinations that could represent the expected trends if all 54 tests were performed. Though the method allowed for a large number of variables to be examined with fewer total tests, the resulting matrix was sparse, and not every condition combination was represented. A summary of the results are shown in Table 5.1, with additional measurements included in Appendix A. Uncertainty levels shown represent measurement uncertainty only, as the data set was not large enough to calculate the values for repeatability. As a preliminary examination of measurement repeatability, six of the eighteen tests were performed a second time. The results from the initial and repeated trials are shown in Table 5.2. Of the six conditions retested, four were within the refrigerant measurement uncertainty of 0.002 g/min. The other two varied by 0.008 and 0.021 g/min. Both of the differing trials occurred with 52% LiBr-water solution and 0.127 mm channels, but there is no physical reason for any correlation.

Table 5.2: Comparison of results from repeated single channel tests.

Trial	Test Conditions				Results	
	$D(mm)$	$\dot{Q}(W)$	$\dot{m}_{in}(g/min)$	$x_{in}(\%)$	$x_{out}(\%)$	$\dot{m}_{ref}(g/min)$
1	0.127	4.98	0.599	52.3	56.0	0.040*
2	0.127	4.98	0.599	52.3	55.2	0.032*
1	0.127	5.96	0.702	52.3	56.8	0.056*
2	0.127	5.96	0.702	52.3	55.0	0.035*
1	0.127	7.04	0.805	52.3	56.0	0.054
2	0.127	7.04	0.805	52.3	55.7	0.050
1	0.127	4.98	0.702	57.1	59.2	0.025
2	0.127	4.98	0.702	57.0	59.3	0.027
1	0.254	7.04	0.702	46.9	50.8	0.054
2	0.254	7.04	0.702	46.9	51.1	0.057
1	0.254	5.96	0.801	51.8	55.4	0.052
2	0.254	5.96	0.801	51.8	55.4	0.052
±	0.005	0.05	0.002	0.1	0.2	0.002

Practically speaking, the data set was too sparse to draw conclusions about unexpected variation in individual tests. However, valuable conclusions are possible concerning measured magnitude and observed trends. Measured refrigerant varied from 0.024 g/min with low heat input rate, low flow rate, high concentration, and high diameter, to 0.065 g/min with high heat input rate, high flow rate, low concentration and low diameter.

The effects of each input variable were examined to deduce how system conditions affect vapor generation rate. Figure 5.4 displays the effect of channel diameter on vapor produced, based on the Taguchi design of experiments discussed above. Rather than varying one condition and holding all other variables at a constant value, the results from all eighteen tests were combined to show the average change caused by a change in channel diameter. Thus, if the effects of all other variables were disregarded, increasing the diameter from 0.127 to 0.254 mm decreased the refrigerant produced by 0.006 g/min, or about 15%. As heat transfer coefficient is inversely

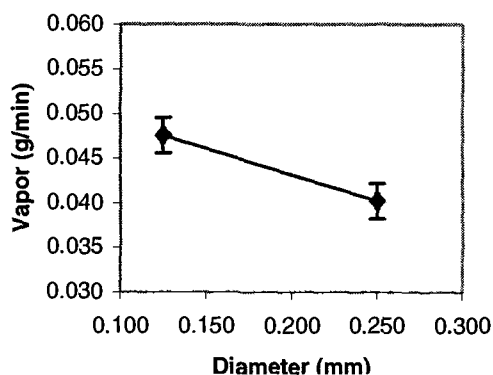


Figure 5.4: Single channel vapor as a function of diameter only, isolated with Taguchi method.

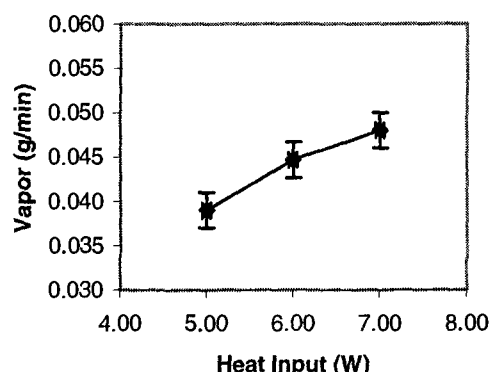


Figure 5.5: Single channel vapor as a function of heat input rate only, isolated with Taguchi method.

related to channel diameter under laminar flow conditions, more rapid boiling is expected to occur in the smaller channel. Further, this result suggests that a decrease in desorber scale can indeed produce a greater amount of vapor both by allowing more channels in a given area, and increasing the vapor produced per channel. Figure 5.5 shows the measured change in water vapor production as a function of heat input rate. Increasing the heat input rate to the channel increased the amount of vapor produced. Note, however, that heat addition provides diminishing returns. Figure 5.6 is a comparison between heat input rate and vapor produced per unit of power. Each additional unit of power produces less vapor than the previous. Thus, a desorber running on lower power would yield more refrigerant per heat input rate, but would also require more channels for the necessary desorption, making the system unnecessarily large.

Figure 5.7 displays the relationship between water vapor produced and lithium bromide concentration, disregarding the effects of the other variables. As the concentration increased, the latent heat of vaporization and saturation temperature

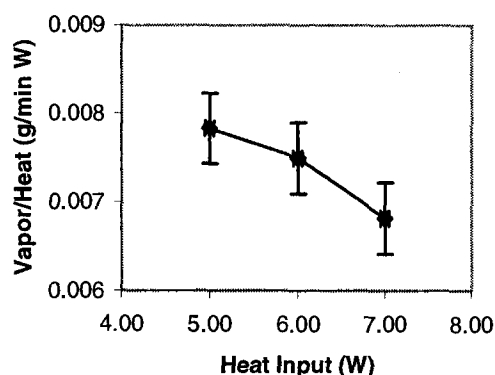
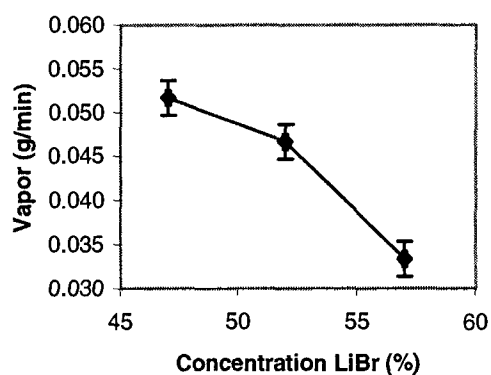


Figure 5.6: Single channel vapor per unit of heat input as a function of heat input rate only, isolated with Taguchi method.



increased. Therefore, higher concentration

Figure 5.7: Single channel vapor as a function of concentration only, isolated Taguchi method.

LiBr-water solutions required greater heat input to produce the same amount of refrigerant. While this trend indicates that a lower concentration solution would increase the efficiency of the desorber, the inverse is true for the absorber, also a vital component of the chiller. In the absorber, the water vapor is reintroduced to the lithium bromide-water solution previously concentrated in the desorber. A high concentration solution has a greater affinity for the vapor than a low concentration solution. So a low concentration in the desorber requires a larger surface area and a larger overall device. Since the absorber is the largest and most complex component in the vapor-absorption cycle (Garimella, 2000), solution conditions are more commonly defined for the highest efficiency in the absorber and not the desorber. Thus the effect of solution concentration shows one situation where the conditions for greatest desorption efficiency are not necessarily the conditions for greatest cycle efficiency.

As shown in figure 5.8, an increase in solution flow rate, disregarding all other variables, caused an increase in vapor flow rate. In this case, increasing the flow rate from 0.6 g/min to 0.8 g/min increased the average rate of vapor production by 0.01

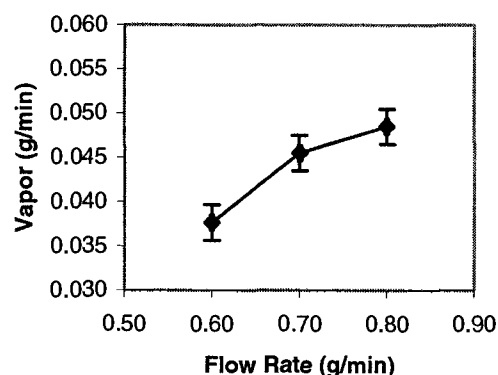


Figure 5.8: Single channel vapor as a function of flow rate only, isolated with Taguchi method.

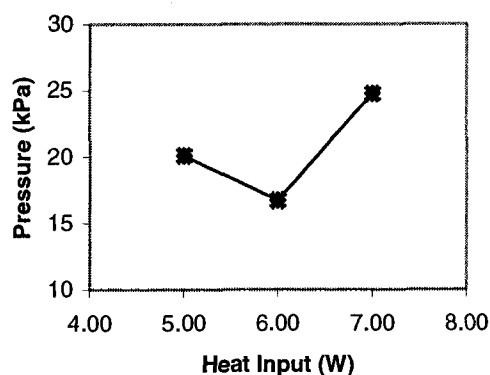


Figure 5.9: Single channel pressure drop as a function of heat input rate only, isolated with Taguchi method.

g/min. Possible reasons for this effect include a change in the boiling regime to a condition more suitable for vapor generation, and greater mixing of solution at the boiling interface, partially countering the concentration gradient previously discussed. However, high solution flow rates are undesirable for two reasons. First, flow rate is directly proportional to pressure required to drive the process. Higher pressures require larger pumps and greater mechanical power inputs. Second, the higher pressure associated with a higher flow rate would increase the saturation temperature of the solution, increasing the energy required to reach saturation conditions. Also, outside the laboratory environment a combustion based vapor-absorption cycle is more practical than an electric. Under combustion heating, higher saturation temperature leads to less temperature difference between the heat source and the solution, increasing the required heat transfer surface area. A higher surface area corresponds to a larger desorber.

Another phenomenon worth noting is shown in Figure 5.9. This graph displays the effect of heat input rate on average measured pressure drop at the channel inlet. While the data is admittedly sparse, the trend shown is consistent and regular. The lowest pressures were recorded for the middle heat input rate, and the highest were recorded for the high heat input rate. This result is non-intuitive, but was previously observed by Zhang et al. (2002). The solution viscosity is a strong function of temperature, and solution always entered the channel in a subcooled state. As the power to the channel heater increased, the average temperature along the length of the channel increased, decreasing the viscosity and required pressure for the portion of the channel still in single phase flow. However, at higher heat input rates a larger portion

of the channel was in two-phase flow and boiling at higher rates, causing a rise in required pressure due to the flow vapor content. Thus each set of flow conditions had a minimum pressure, though that minimum did not necessarily correspond with an ideal desorption rate.

Table 5.3 summarizes the pressure measurements for the 18 conditions studied. Pressure was measured at the channel inlet by an oil-filled transducer at 100 Hz and averaged over 45 seconds. Time series graphs of the pressure data are included in Appendix C. The dominant parameter for flow pressure was diameter, as would be expected, with an order of magnitude difference in pressure between the two diameters

Table 5.3: Summary of pressure drop data for single microchannel flow boiling, averaged over 45 seconds.

Test Conditions				Results	
$D(mm)$	$\dot{Q}(W)$	$\dot{m}_{in}(g/min)$	$x_{in}(\%)$	$\Delta P(kPa)$	$Deviation(kPa)$
0.127	4.98	0.598	46.2	22.34	0.055
0.127	5.96	0.698	46.2	25.79	0.062
0.127	7.04	0.795	46.3	28.21	0.090
0.127	4.98	0.599	52.3	24.55	0.269
0.127	5.96	0.702	52.3	27.72	0.103
0.127	7.04	0.805	52.3	49.59	0.221
0.127	4.98	0.702	57.1	68.00	0.207
0.127	5.96	0.798	56.9	36.55	0.207
0.127	7.04	0.603	56.9	49.31	1.745
0.254	4.98	0.799	46.9	1.72	0.028
0.254	5.96	0.602	46.9	4.34	0.014
0.254	7.04	0.702	46.9	6.34	0.014
0.254	4.98	0.697	51.7	1.38	0.021
0.254	5.96	0.801	51.8	1.52	0.014
0.254	7.04	0.595	51.7	4.76	0.021
0.254	4.98	0.795	56.6	2.28	0.069
0.254	5.96	0.601	56.6	3.52	0.055
0.254	7.04	0.698	56.7	5.31	0.069
± 0.005	± 0.05	± 0.002	± 0.1	± 0.4	

in a microchannel desorber area, but requires four times as much space. From a practical standpoint, an array of 50 channels at 0.254 mm diameter would be about three times the size of an array of the same number of 0.127 mm channels if the channel spacing were constant. However, much of the size increase could be in array thickness. For most applications the width is a greater constraint than thickness. Further, increasing the flow rate in the larger tubes to a level proportional to the larger area yielded pressures comparable to those found in 0.127 mm channels, but with a lower vapor produced per area per Watt, 1.8×10^5 versus 7.6×10^5 g/(min•m²•W). A summary of the results from the higher flow rate tests are included in Appendix A.

The pressure during flow boiling is generally quite steady, as illustrated by the low standard deviations displayed in Table 5.3. The standard deviation exceeded 1% of the overall magnitude in only five of the 18 cases, with the largest of 4% at low channel diameter, high heat input rate and high concentration. However, four of those five cases with higher deviation occurred at the highest inlet concentration, which is

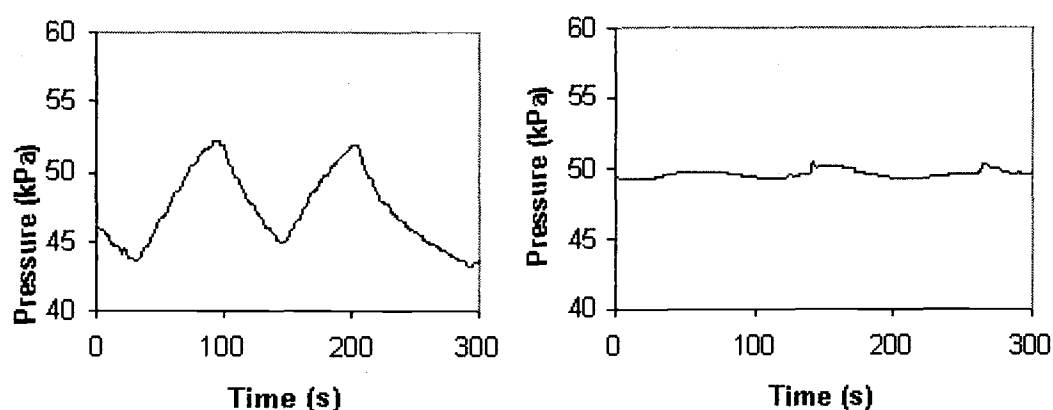


Figure 5.10: Comparison of pressure drop over time between 7.04 W, 0.603 g/min, 56.9% LiBr and 7.04 W, 0.805 g/min, 52.3 % LiBr, both with 0.127 channel.

the most likely condition for a practical desorber. Therefore, any flow source for use in a microchannel desorber must be capable of adjusting for a 5% standard deviation in required flow pressure as the desorption occurs. The largest deviation occurred under high heat flux and low flow rate. As shown in Figure 5.10, rather than varying within a small range, measured pressure for this condition oscillated repeatedly and steadily by as much as 15 kPa. This flow regime is common in microchannel boiling, and is discussed further in Chapter 6. Tests by Hetsroni et al. (2003), Li et al. (2003), and Peles (2003) recorded high frequency pressure variations during boiling, but none were documented here. It is likely that though the pressure transducer response time was 200 Hz, the trapped gases in the flow system damped any high frequency signals.

Table 5.4: Summary of ideal heat requirements and calculated losses for single channel desorber.

Test Conditions				Results		
$D(mm)$	$\dot{Q}(W)$	$\dot{m}_{in}(g/min)$	$x_{in}(\%)$	$\dot{m}_{ref}(g/min)$	$\dot{Q}_{ideal}(W)$	$\dot{Q}_{loss}(W)$
0.127	4.98	0.598	46.2	0.053	3.41	1.57
0.127	5.96	0.698	46.2	0.056	3.75	2.21
0.127	7.04	0.795	46.3	0.065	4.26	2.78
0.127	4.98	0.599	52.3	0.040	2.68	2.30
0.127	5.96	0.702	52.3	0.056	3.42	2.53
0.127	7.04	0.805	52.3	0.054	3.49	3.55
0.127	4.98	0.702	57.1	0.025	2.18	2.80
0.127	5.96	0.798	56.9	0.044	2.96	3.00
0.127	7.04	0.603	56.9	0.035	2.17	4.87
0.254	4.98	0.799	46.9	0.046	3.39	1.59
0.254	5.96	0.602	46.9	0.036	2.56	3.40
0.254	7.04	0.702	46.9	0.054	3.25	3.79
0.254	4.98	0.697	51.7	0.040	3.03	1.95
0.254	5.96	0.801	51.8	0.052	3.72	2.24
0.254	7.04	0.595	51.7	0.038	2.74	4.30
0.254	4.98	0.795	56.6	0.030	2.49	2.49
0.254	5.96	0.601	56.6	0.024	1.93	4.03
0.254	7.04	0.698	56.7	0.042	2.83	4.21
±0.005	±0.05	±0.002	±0.1	±0.002	±0.01	±0.03

Heat losses were estimated using the calculated enthalpies as discussed above, and Table 5.4 shows a summary of the calculated losses for each of the tests performed. Enthalpy calculations for each solution state are included in Appendix A. Losses varied from 31% to 58% for the conditions examined, with heat losses from 1.5 to nearly 5 Watts depending on flow conditions, despite the Teflon and cork insulation enclosing the desorption system. These heat loss levels indicate that better insulation, lower heater temperatures, or increased channel density could decrease the heat input rate required for vapor production by 32% to 58%, or increase the vapor produced for a given heat input rate.

6. Multi-Channel Desorption

6.1 *Experiment Set-up*

As mentioned above, a single channel test provides specific and detailed information on microchannel behavior, but is more useful if the results scale in a predictable way into a multi-channel array. Further, if the solution and heater temperatures are unchanged in the scaling process, heat loss levels should remain nearly constant, despite the increase in overall heat addition. Therefore, a multi-channel system should be capable of far lower proportionate losses than a single channel desorber. For these reasons an array of ten microchannels was tested under conditions as similar as possible to the single channel tests to examine how the single channel results may relate to the function of a full scale desorber. The mass flow rate was increased tenfold, while the heat input rate was increased in a manner described below. As the higher flow rate was not feasible for the syringe pumps, flow was provided by a positive displacement gear pump, fitted with PEEK gears and titanium housing for corrosion resistance. The flow loop for multi-channel testing is shown in Figure 6.1. The flow controls for the pump at this low flow rate were crude, so an additional metering valve with a fluid bypass loop was necessary to more precisely control the fluid flow rate. However, the increased flow rate used for the multi-channel testing brought the uncertainty for flow measurement in the Coriolis flow meter to less than 1% for a time averaged test. The Coriolis flow meter measured density, temperature and flow rate, before the fluid entered the titanium preheater.

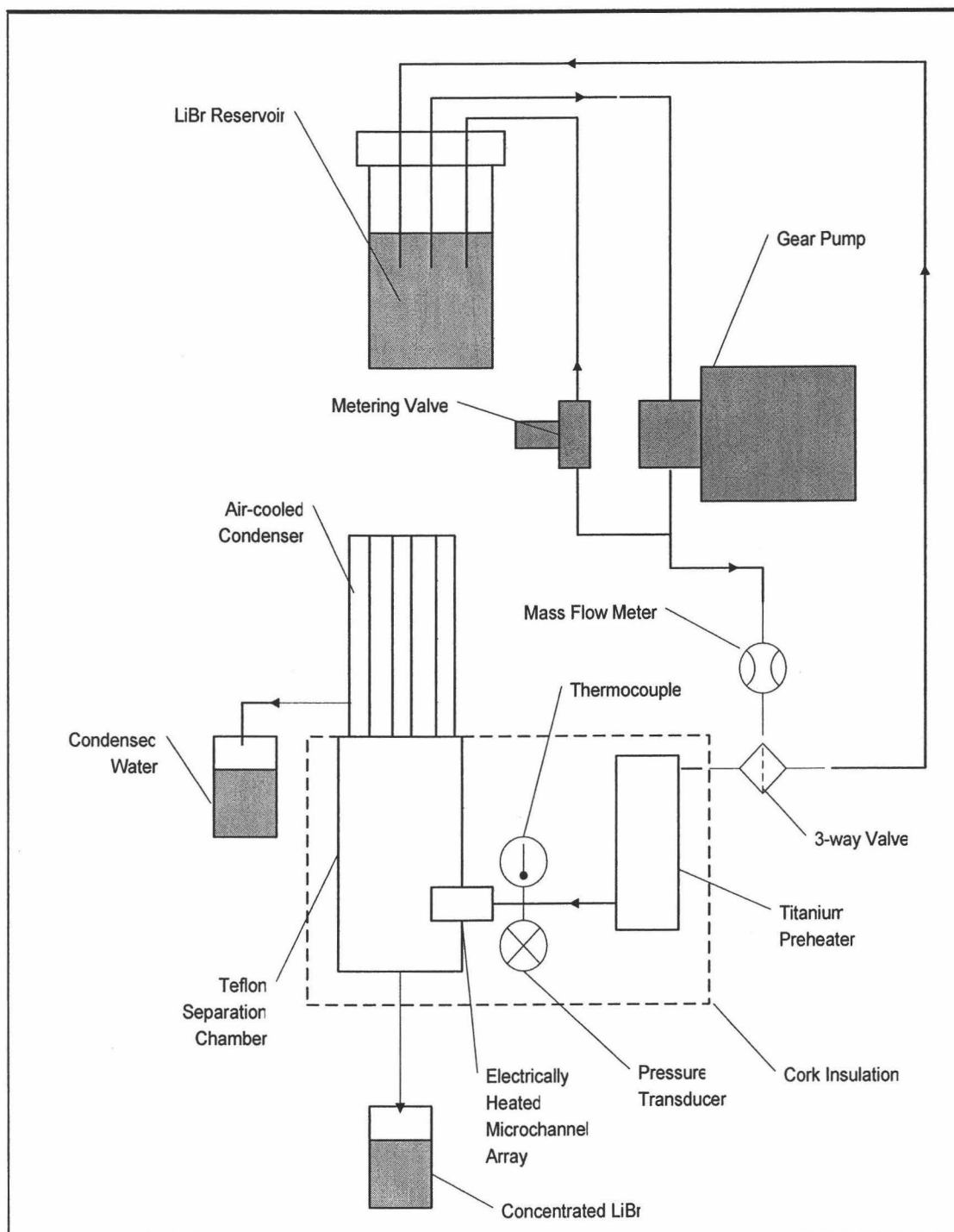


Figure 6.1: Schematic of test set-up for multi-channel desorption tests.

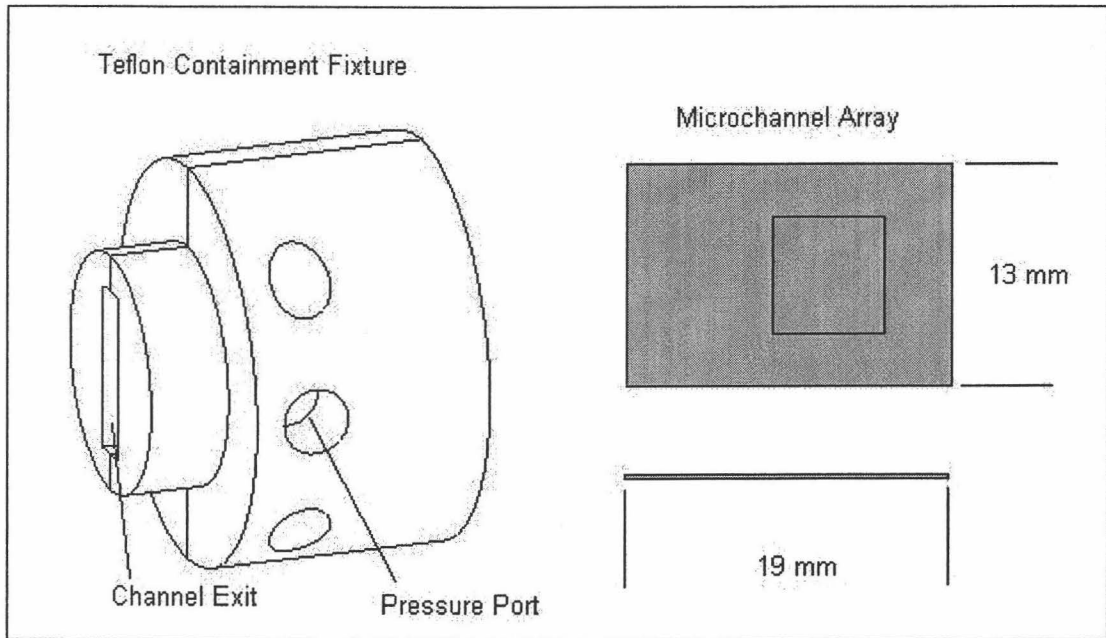


Figure 6.2: Multi-channel desorber array and containment fixture.

Fluid was heated within the preheater to a level well below saturation due to the working temperature of the flow components. The flow path from the preheater required flexible tubing to make the necessary connections, and the PEEK tubing used could not withstand temperatures above 100 °C for sustained periods. Temperatures measured at the channel inlets varied from 65 to 74 °C.

For the channels themselves, a pair of titanium arrays was manufactured by Tom Tseng of the Oregon State University Industrial Engineering and Manufacturing Department by sandwiching layers of thin titanium sheets. A representation of these channel arrays and their containment fixture is shown in Figure 6.2. Each of the titanium sections contained five rectangular microchannels, 8.5 mm long and 1 mm apart, laser cut into the titanium layers before diffusion bonding. Figure 6.3 displays an image of a microchannel exit, 0.143 mm x 0.124 mm, yielding a hydraulic diameter of 0.133 mm.

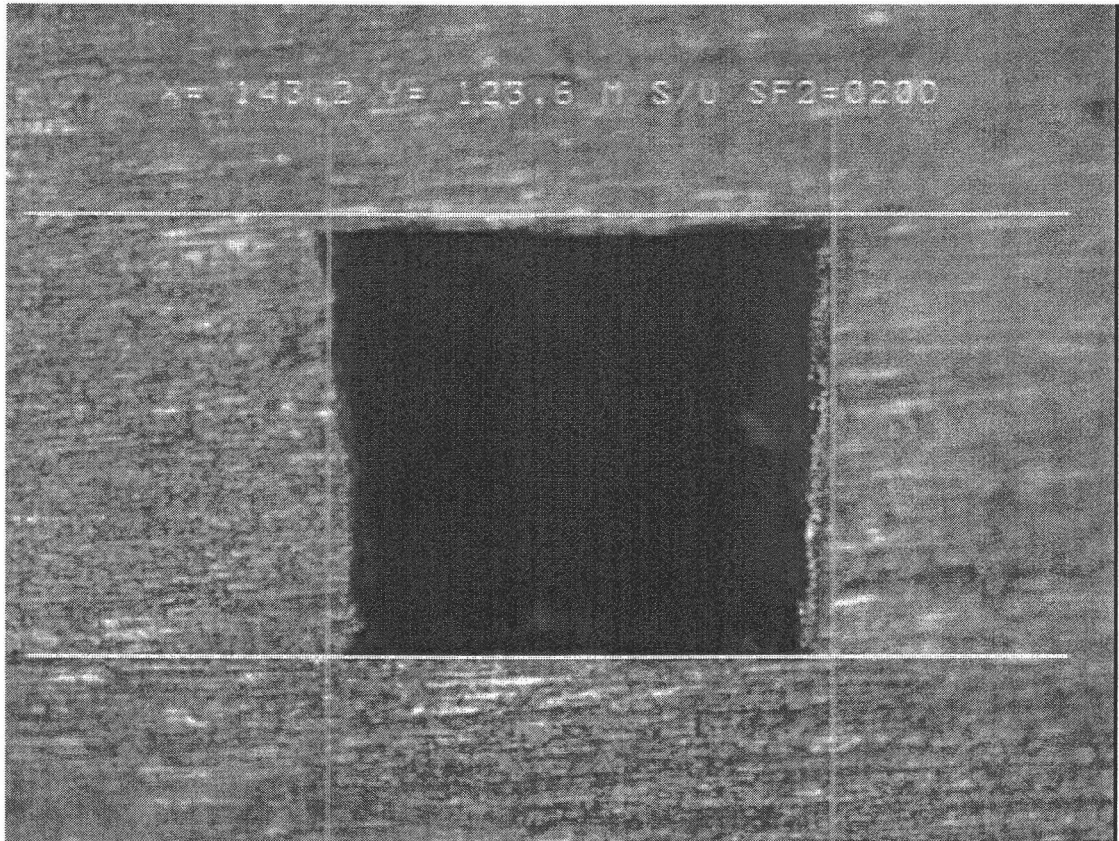


Figure 6.3: Photograph of exit of 0.132 mm microchannel, provided by Tom Tseng.

A larger, rectangular opening on the face provided a fluid entrance for the channels, while flow exited from the narrow edge. These channel arrays were arranged on opposing sides of a Kapton heater, and held within a Teflon containment fixture, also shown in Figure 6.2, that provided the fluid fittings and a small reservoir for each titanium array. Temperature and pressure were measured within the fluid reservoirs to establish entrance conditions and pressure drop. Next, the boiling solution was expelled into the same Teflon separation chamber used for single channel testing, and refrigerant and solution were collected in a similar manner.

6.2 Procedure

The multi-channel experimental procedure was much like the single channel procedure, but differed in the following ways. The pump controls were awkward for the required flow rate, and the flow was highly variable. Therefore, only one nominal flow rate was tested, and the actual flow rate differed slightly between measurements. As previously mentioned, it was not possible to scale the heat input rate fully in the multi-channel array for three reasons: first, the bonded channel arrays provided one wall of the fluid reservoir, making boiling occur within the reservoir at high heat fluxes. Second, due to the bypass loop mentioned above, the pump assembly provided a pressure source, rather than a flow source. However, as the rate of boiling increased, the pressure required for sustained flow increased suddenly, approximately doubling in a period of several seconds. This sudden rise in required pressure made the flow rate uncontrollable with the flow system used. Finally, the bonding technique used to manufacture the titanium channels limited the channel length to 8.5 mm, compared to the 25 mm in the single channel testing. While the multi-channel arrays required less of their length for fittings and connections, still less total area was available for heat transfer within the channels. Also, vapor and concentrated solution were collected for 5 minutes instead of the 20 minutes for single channel due to the higher total volume of fluid. The decrease in measurement time increased the uncertainty from 0.002 g/min of vapor to 0.006 g/min, or from 4% of the measured value to 7%.

Extensive testing with these micro-channel arrays illustrated an inherent instability within the system design, further limiting the maximum heat input rate. The pair of five channel arrays allowed for a more compact desorber design, and a

more uniform load on the electric heater. By removing heat from both sides of the Kapton resistance heater higher heat fluxes were possible without burnout, and less heat was lost due to conduction through surrounding insulation. The flow path was evenly split between the two channel arrays, each ideally supplied with the same pressure source and fluid flow. But despite care in manufacturing, minor variations existed in the fittings, tubes, reservoirs and channels, making the flow rates slightly different for the two channel arrays. At low heat input rates, this difference was not a large concern, as the higher flow rate in the less constricted path balanced the pressure drop variation with only a small difference in fluid flow. However, at high heat fluxes the path with lower flow rate heated faster and boiled sooner, further increasing the difference in pressure requirements. Soon, the flow differential produced an escalating temperature variation between the alternate flow paths, and flow in the hotter nearly ceased, likely due to the pressure drop from the high boiling rate and lithium bromide crystallization. Thus, minor differences due to manufacturing and assembly were apparently magnified under working conditions until they dominated the flow conditions. Further, the length limitation imposed by the manufacturing technique increases the required heat flux, imparting even greater boiling differences to small flow variations. Therefore, practical, high flux systems will either need to be built with exceptional tolerances and care, or a different flow design must be found that would evenly distribute both the heat and the fluid. However, the greatest source of instability in this test was the paired array of microchannels. A single reservoir and a single array of channels would greatly diminish differences in flow, but would require a more durable heating system.

6.3 Results & Discussion

Table 6.1 contains a summary of the data collected from the multichannel desorption tests. The final two test configurations proved to be too unstable for accurate data collection. Further, as mentioned above, the multi-channel tests did not scale from the single channel tests. The increase in heat input rate could not match the increase in flow rate. The most valuable information gained from these preliminary multi-channel tests was that limitations due to manufacturing and scale unsettled an already unstable system, making the transition from single channel systems to micro-channel arrays far more complex than anticipated.

Table 6.1: Summary of multi-channel desorption tests.

Test Conditions				Results		
$D(mm)$	$\dot{Q}(W)$	$\dot{m}_{in}(g/min)$	$x_{in}(\%)$	$x_{out}(\%)$	x_{diff}	$\dot{m}_{ref}(g/min)$
0.133	21.92	7.10	47.6	48.3	0.6	0.092
0.133	24.92	7.08	47.0	47.7	0.7	0.109
0.133	27.92	6.90	47.4	48.6	1.2	0.169
0.133	21.92	7.20	52.2	52.9	0.7	0.099
0.133	24.92	7.13	52.0	52.7	0.8	0.107
0.133	27.92	7.10	52.4	53.4	1.1	0.142
0.133	21.92	6.98	57.2	57.9	0.7	0.082
0.133	24.92			Unstable		
0.133	27.92			Unstable		
± 0.005	± 0.05	± 0.06	± 0.1	± 0.2	± 0.2	± 0.006

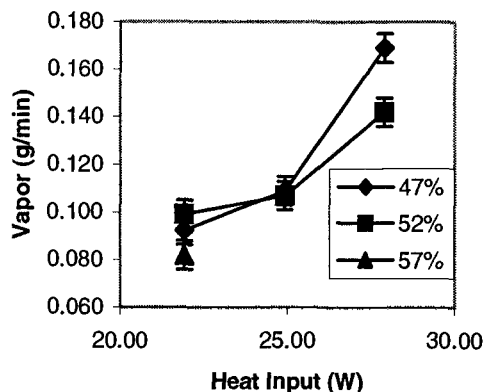


Figure 6.4: Multi-channel vapor as a function of heat input rate and concentration.

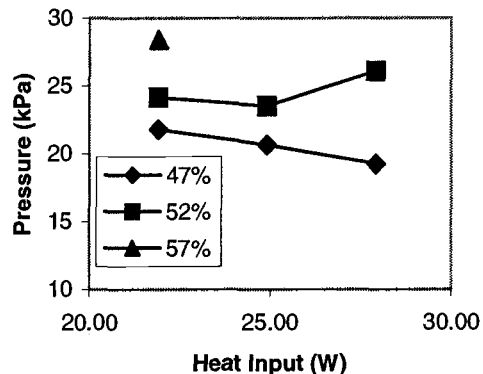


Figure 6.5: Multi-channel pressure as a function of heat input rate and concentration.

Despite the flaws in this data set, there is some useful information. Figure 6.4 shows the collected vapor based on heat input rate and concentration. Since only one flow rate and channel diameter was studied, it is possible to compare the values directly rather than requiring statistical processing. As observed with the single channel test, an increase in heat input rate caused an increase in vapor produced. Under most conditions examined here, differences in vapor produced based on concentration were within the calculated uncertainty, with the only exception being the highest heat flux. While magnitude of vapor could not be directly compared to single channel tests, the trend was the same.

Figure 6.5 displays pressure drop as a function of heat input rate and concentration. Since viscosity is a function of concentration, the pressure would be expected to be higher for higher concentrations, as observed here. However, no conclusions were possible from the heat input rate relationship. As discussed above, heat addition increases temperature, decreasing fluid viscosity and pressure drop until boiling begins. With the low heat flux supplied to the channels in this test, pressure

should have decreased with increased heat. While that pattern was not found here, there was not enough data to make any definite statements about this pressure drop-heat input rate relationship.

Table 6.2 contains a summary of the calculated heat requirements and efficiencies for the multichannel tests, based on the same methods used for single channel tests. Note that the calculated heat losses are entirely unreasonable. It must be recalled that this test was performed with a lower preheat temperature due to the addition of PEEK tubing at the preheater exit. Thus much of the heat input to the microchannel went to sensible heating before boiling could begin. This additional power requirement meant that a smaller portion of the heat input into the microchannel went to boiling the solution when compared to single channel tests. The variation in heating led to some unexpected calculated thermodynamic results.

Table 6.2: Summary of ideal heat requirements and calculated losses for multichannel desorber.

Test Conditions				Results		
$D(mm)$	$\dot{Q}(W)$	$\dot{m}_{in}(g/min)$	$x_{in}(\%)$	$T_{in}(^{\circ}C)$	$\dot{Q}_{ideal}(W)$	$\dot{Q}_{loss}(W)$
0.133	21.92	7.10	47.6	65	23.57	-1.65
0.133	24.92	7.08	47.0	65	23.84	1.08
0.133	27.92	6.90	47.4	65	25.72	2.20
0.133	21.92	7.20	52.2	66	25.96	-4.04
0.133	24.92	7.13	52.0	66	25.89	-0.97
0.133	27.92	7.10	52.4	68	26.76	1.16
0.133	21.92	6.98	57.2	74	24.55	-2.63
0.133	24.92		Unstable			
0.133	27.92		Unstable			
± 0.005	± 0.05	± 0.06	± 0.1		± 0.07	± 0.3

One would expect the heat loss to decrease as the size scales upward, but values below zero indicate a problem with the ideal model or a mistake in the measurement process. In this case, the ideal model contains several assumptions about the conditions inside the microchannel. First, it assumes that the temperature in the reservoir is uniform. While a large reservoir allows for an even pressure distribution to the channel array, it does not contribute favorably to an even temperature. Second, and more important, the model assumes that vapor is produced at saturation temperature. Therefore, it assumes that all of the solution exits the microchannel at the calculated boiling temperature for the system pressure. Possible conditions to invalidate this assumption include subcooled boiling and uneven flow distribution. In subcooled boiling, a high heat transfer coefficient rapidly heats the solution in contact with the walls, which can begin to boil before the bulk fluid is fully heated. Thus vapor can be produced with the bulk temperature still below saturation. While this is possible, the small scale of the microchannel makes it unlikely. The heat transfer coefficient would have to be unreasonably high to maintain a large temperature gradient within the channel. The more likely conclusion is that the flow rates differed between the channels. The instability in the system is compelling evidence that the parallel flow paths received different amounts of solution. It is then likely that all of the boiling occurred in the channel array with the lower flow rate, with all of the vapor produced from one array of channels. This imbalance would allow for a large portion of the flow to never be heated to saturation temperature, even as vapor was being produced elsewhere. So, the true efficiency may be higher than the 60% commonly encountered in single channel tests, but it is certainly not beyond 100%, as often calculated here.

7. Infrared Visualization

7.1 Experiment Set-up

The single and multi-channel tests described above included global measurements and time-averaged results, but neither examined the condition of the boiling solution directly. As fluid boils in a channel, it can transition between several distinct regimes, each with defined flow and pressure characteristics. The ideal method to study boiling regimes requires a transparent channel and high speed imaging. However, replacing a channel wall with glass or plastic changes the heating characteristics of a system. Therefore, to better understand the flow conditions within a microchannel desorber, the exit condition of the solution was examined with an infrared imaging system, equipped with a 10x microscope objective. The visualization of the exit condition of the LiBr-water solution can potentially provide information on the boiling regime at the channel exit, and the ideal conditions for desorption to occur. Further, by studying a thermal image it may be possible to establish if equilibrium conditions exist at the channel exit.

Figure 7.1 shows a schematic representation of the flow system used for the thermal visualization. Tests were performed using the preheater that was used in the multi-channel tests, the insulation and flow system that were used for single channel tests, and a single 0.127 mm channel. To obtain the exit images, the condenser was removed and replaced with a thermal video system, capable of recording thermal radiation images at 120 Hz. Images were recorded at 120 Hz and two shutter speeds for twelve conditions: two concentrations, two flow rates and three heat inputs rates.

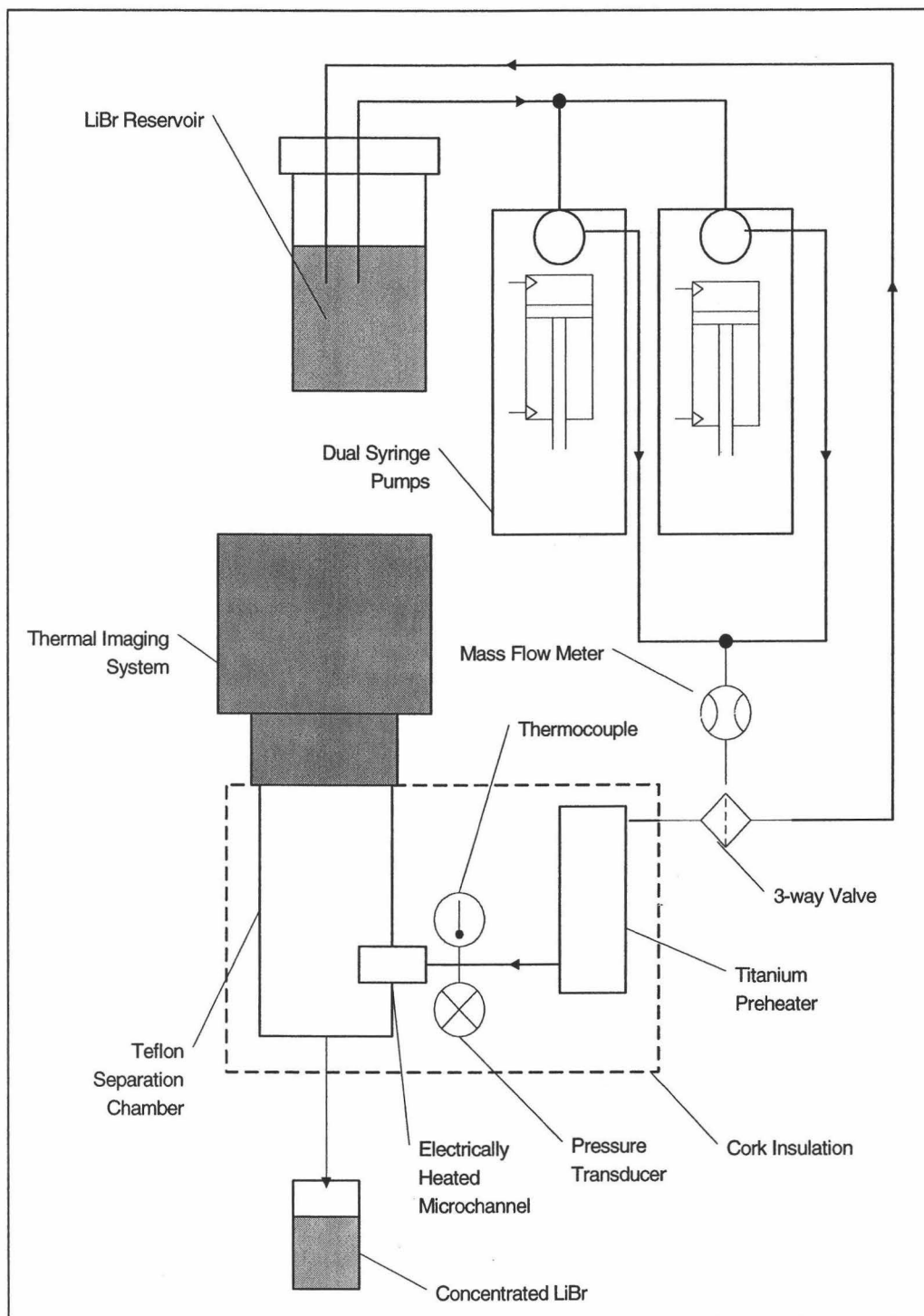


Figure 7.1: Schematic of test set-up for infrared visualization.

7.2 Procedure

The test procedure for thermal visualization was similar to that used for single channel desorption. The syringe pumps were set to produce a constant flow rate and the system was allowed to reach a steady temperature, with heat supplied by both the preheater and the microchannel heater. When steady temperatures were reached, the thermal imaging system was placed above the exit of the channel to document exit conditions. A vacuum pump removed the vapor from the separation chamber to insure that the lens remained clear. Images were recorded at 120 Hz for eight seconds while pressure distribution was independently recorded at 100 Hz for the same time period. Tests were repeated for two shutter speeds to capture both high and low speed phenomena.

7.2 Results and Discussion

Table 7.1 displays a summary of the observed exit conditions. For the twelve cases tested, flow observations can be classified into four categories: a) steady dripping from channel exit at low heat input rates; b) unsteady dripping with occasional vapor at moderate heat input rates; c) continuous spraying of fine droplets at high heat input and flow rates; and d) long period oscillating between unsteady two-phase drip and steady spray at high heat input and low flow rates. All conditions were recorded at 120 Hz with shutter speeds of 0.0644 and 1.256 ms, to capture both the rapid droplet sprays and the more gradual drips respectively. The low shutter speed produced clearer images and lower uncertainties, while the high shutter speed returned

sharper images of vapor and droplet dispersion. Thermal images for each test are included in Appendix E.

Table 7.1: Summary of observed exit conditions for single channel infrared visualization.

Test Conditions				Results	
#	$x_{in}(\%)$	$\dot{Q}(W)$	$\dot{m}_{in}(g/min)$	$P(kPa)$	Exit Flow Observation
1	47.0	4.98	0.603	34.4	Steady Drip
2	47.0	5.96	0.603	26.4	Unsteady Drip
3	47.0	7.04	0.603	36.3	Oscillating
4	47.1	4.98	0.801	44.6	Unsteady Drip
5	47.1	5.96	0.801	67.1	Unsteady Drip
6	47.1	7.04	0.801	80.3	Droplet Spray
7	57.0	4.98	0.607	39.8	Steady Drip
8	57.0	5.96	0.607	36.6	Unsteady Drip
9	57.0	7.04	0.607	57.9	Oscillating
10	57.4	4.98	0.803	59.8	Steady Drip
11	57.4	5.96	0.803	56.0	Steady Drip
12	57.4	7.04	0.803	53.3	Unsteady Drip
unc	0.1	0.05	0.002	0.4	

In general, low heat flux led to a steady drip. Under these conditions, boiling either was not occurring at all, or was occurring at too low of a rate to alter the exit condition from that of single phase flow. Note, however, that vapor was still produced for these test cases, despite the lack of evidence for boiling. In these circumstances, the solution temperature was high enough to allow for vapor evaporation, but may not have been high enough to cause two-phase flow. Figure 7.2 displays thermal images for a steady drip outlet condition produced in Test #7. The white outline indicates the channel exit. Each image displays an area 2.36 mm x 2.54 mm.

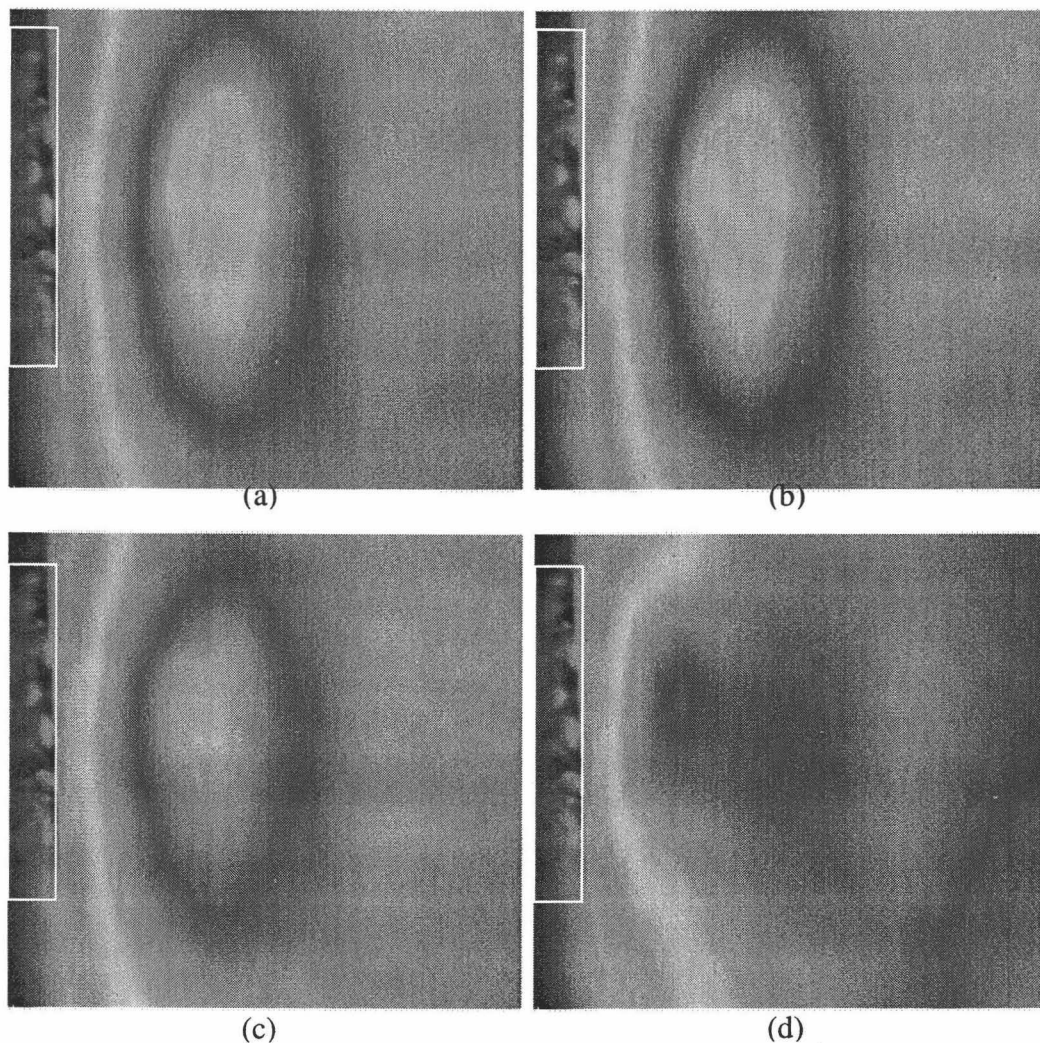


Figure 7.2: Thermal visualization of steady drip exit conditions, 57.4% LiBr solution, 5.96 W, 0.803 g/min. 1.256 ms shutter speed, consecutive images 25 ms apart.

For most cases, when heat flow was increased the condition changed gradually from a steady drip to an unsteady two-phase drip. The heat flux required for this transition varied depending on flow rate and concentration, with high flow rates and concentrations needing more heat to cause the change. The unsteady two-phase drip state was characterized by a constant liquid layer covering the exit of the channel, with

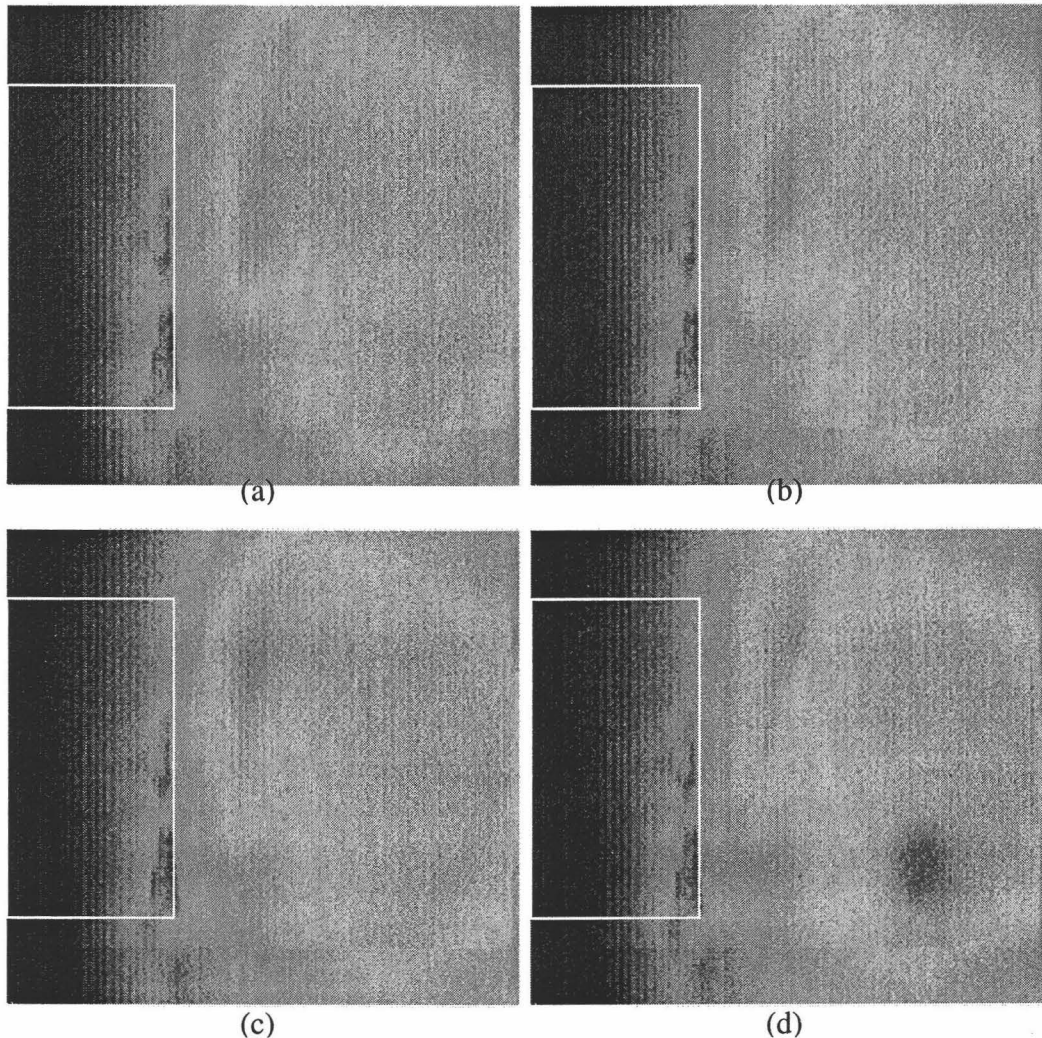


Figure 7.3: Thermal visualization of unsteady drip exit conditions, 47.0% LiBr solution, 5.96 W, 0.603 g/min. 0.0646 ms shutter speed, consecutive images 8 ms apart.

both drips and sprays occasionally exiting the channel. Figure 7.3 shows an example of the unsteady drip condition, is observed with Test #4.

The oscillating condition involved the most dramatic changes in flow conditions. At low flow rates and high heat fluxes the flow did not settle on a single regime. Rather it alternated between unsteady two-phase drip conditions and droplet spray conditions, with a period that varied between 45 and 90 seconds. Since pressure

varies based on flow boiling conditions, the measured pressure during oscillating flow varied by as much as 14 kPa, with the pressure climbing during droplet spray

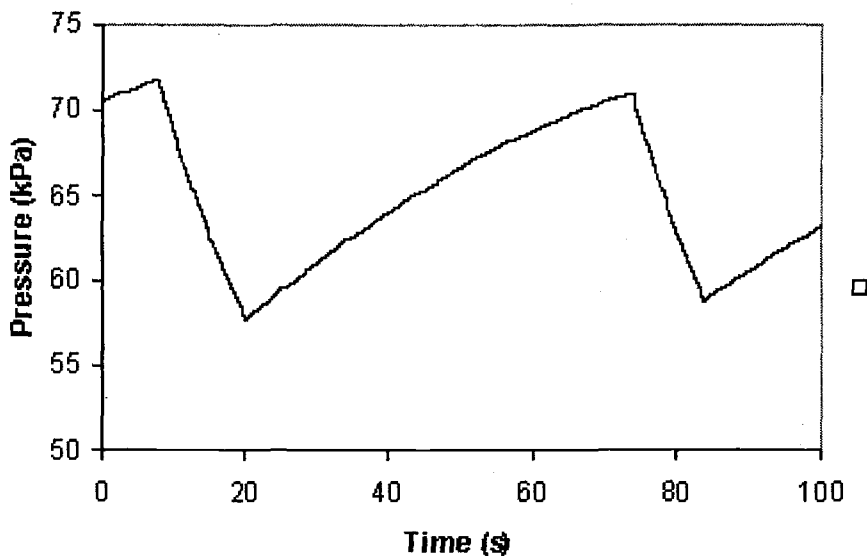


Figure 7.4: Pressure distribution of oscillating exit conditions, 47.0% LiBr solution, 7.04 W, 0.603 g/min.

conditions and falling during unsteady drip conditions. Figure 7.4 shows the pressure changes during alternating conditions, in this case Trial #3. This long period oscillation has been previously observed and explained by Peles (2003), and it is likely caused by trapped gases in the flow loop. The change in boiling regime can be sudden, as observed by Steinke and Kandlikar (2003), Li et al. (2003), and Jeong et al. (2003). With an entirely incompressible system, the response to pressure drop change would be instantaneous. However, even the smallest voids would slow the system pressure response, causing the pressure required to maintain a constant flow rate to

increase faster than the system response. The flow rate would fall at the beginning of the cycle, then rise as the pressure increased until the flow rate was sufficient to

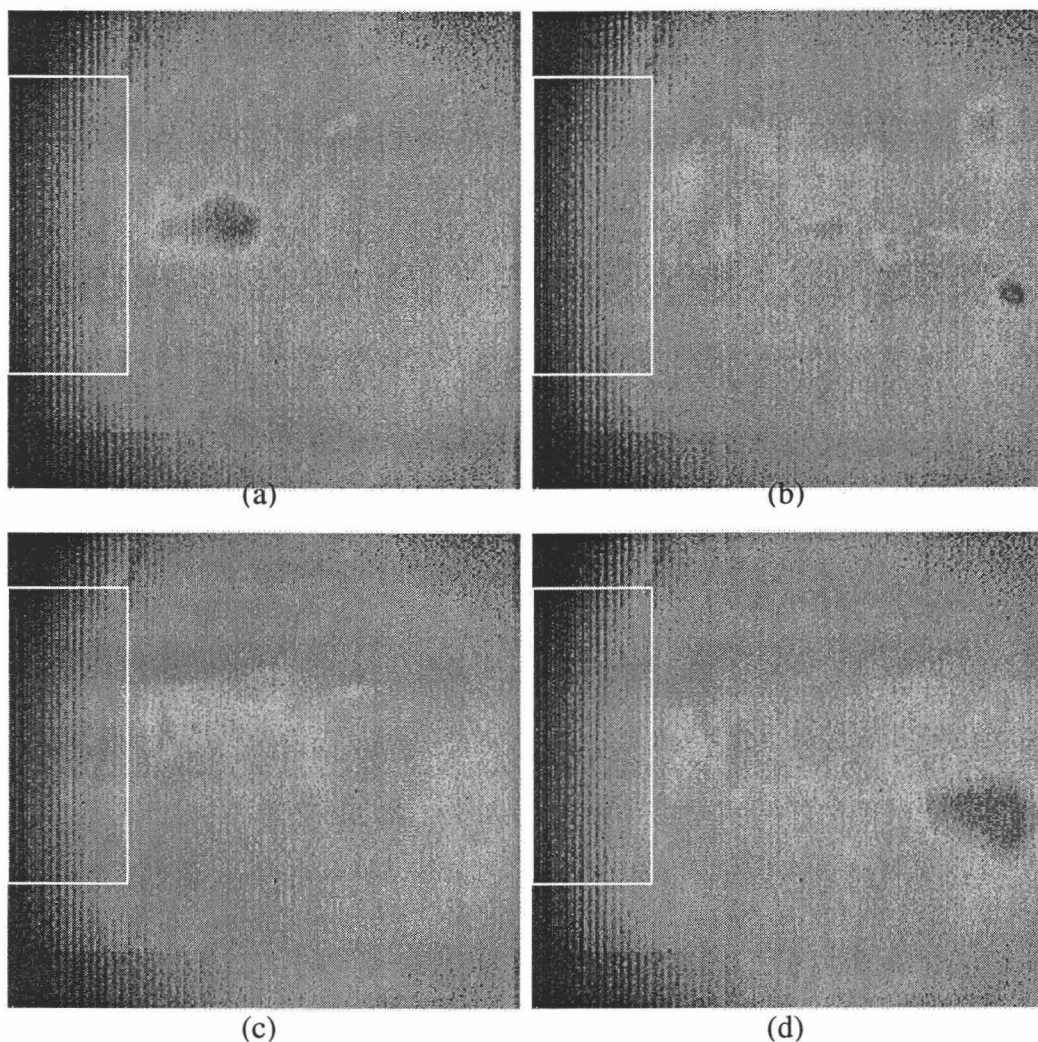


Figure 7.5: Thermal visualization of droplet spray exit conditions, 47.1% LiBr solution, 7.04 W, 0.801 g/min. 0.0646 ms shutter speed, consecutive images 8 ms apart.

decrease the boiling rate. At this point the boiling would cease and the pressure would fall. These oscillations could be avoided by removing all trapped gases from the

system and using only rigid flow conduits. Further, addition of heat or a higher flow rate can cause a transition to a constant droplet spray exit condition.

When the flow rate and heat flux were sufficiently high the flow system remained in droplet spray conditions rather than oscillating. Figure 7.5 displays the thermal images for droplet spray, produced in Test #6. Under these conditions, solution exited the channel in sustained bursts of vapor and solution, with no liquid layer covering the channel outlet. While this spray produced the largest amount of vapor, it required the largest pressures, 80 kPa. All pressure variations in this condition were within the uncertainty of the pressure transducer, but higher frequency signals may have been damped by air in the preheater or the supply line.

These observations indicate that exit condition is a function of all three of the tested variables: flow rate, concentration and heat flux. Further, it appears that boiling rate increases with an increase in heat flux, or decrease in flow rate or concentration.

8. Application

To establish the utility of the desorber tested, the results were compared to a model LiBr-water vapor-absorption chiller capable of transferring 150 W at 20 °C. The refrigerant mass flow rate necessary for 150 W to be transferred through the evaporator can be calculated

$$\dot{m} = \frac{\dot{Q}}{h_{out} - h_{in}} \quad (5)$$

where enthalpy values are for saturated vapor at exit and saturated liquid at inlet, both at 2.4 kPa, a common evaporator pressure. Using this method, required refrigerant was calculated to be approximately 4 g/min.

The current standard for desorption systems in commercial applications is internal falling film desorbers. These devices separate vapor from solution by letting a thin film flow within the inner surface of an array of tubes. When the tubes are heated, usually by steam or combustion byproducts, the refrigerant evaporates and travels up the core of the tube for collection. The thin film allows for high rates of heat transfer, and the large, open core allows for efficient removal of the produced vapor. However, this design is often too bulky for portable applications. Numrich (1995) developed and evaluated a method for estimating the heat transfer surface area required for a falling film desorber, where

$$A = \frac{(\dot{H}_{out,s} + \dot{H}_{out,ref}) - \dot{H}_{in,s}}{\dot{q}} \quad (6)$$

For falling film conditions, the chief transport resistance is in the falling film itself.

Thus, the energy term in Equation 7 can be represented,

$$\dot{q} = \alpha(T_h - T_s) \quad (7)$$

The heat transfer coefficient for these circumstances is a function of Nusselt Number, as shown in Equation 8.

$$Nu = \frac{\alpha(\nu_s^2/g)^{\frac{1}{3}}}{k} \quad (8)$$

For the flow conditions of interest, the correlations related by Mills (1992), the film Reynolds number is

$$Re = \frac{4\Gamma}{\mu_s} \quad (9)$$

where

$$\Gamma = \frac{\dot{m}}{\pi D} \quad (10)$$

Under these laminar film conditions, the Nusselt Number can be approximated by

$$\bar{Nu} = \frac{4}{3} \left[\frac{Pr_s (\nu_s^2 / g)^{1/4}}{4Ja_s L} \right] \quad (11)$$

Table 8.1 summarizes calculations for desorber size based on a 150W, single-effect LiBr-water heat pump. LiBr-water solution properties come from McNeely (1979), Lee, et al. (1990) and DiGuilio (1990). According to this model, a falling film desorber capable of supplying the required 4 g/min of vapor from 80 g/min of solution would require an array of 225 20 cm long, 1 cm diameter tubes, producing a device 22 cm tall and 22 cm on a side. Note that the above calculations assume atmospheric pressure within the desorber to allow for a closer comparison to the microchannel desorber tested. A desorber modeled under a more conventional pressure of 8.7 kPa, as presented by ASHRAE Fundamentals Handbook (1997), produces a component with a tube length of 35 meters. These 35 m of tubing could be packaged into a 14 x 14 tube array, 20 cm tall and 21 cm on a side. A desorber of this size is reasonable for most applications, and has the advantage of being entirely gravity driven. However, when a small size is necessary, a microchannel system can provide the necessary vapor with far less volume.

Table 8.1: Summary of model for predicting falling film desorber size.

Process Constraints			
Inlet Temperature	140 °C	Steam Temperature	200°C
Inlet Concentration	57%	Outlet Concentration	60%
Solution Flow Rate	80 g/min	Vapor Flow Rate	4 g/min
Tube Diameter	0.01 m	Desorber Pressure	101 kPa
Number of Tubes	225		
Flow Conditions (per tube)			
Solution Conductivity	0.489 W/m·K	Solution Viscosity	0.0012 m ² /s
Solution Density	1587 kg/m ³	Specific Heat	1900 J/kg·K
Prandtl Number	4.5	Film Thickness	0.0004 m
Flow Rate per Unit Width	0.0002 kg/s·m	Film Reynolds Number	0.5
Nusselt Number	0.066	Heat Transfer Coefficient	613 W/m ² ·K
Thermodynamic Results (per tube)			
Inlet Enthalpy	1.44J	Outlet Enthalpy	2.34 J
Required Transfer Area	0.0115 m ²	Tube Length	0.18 m

The single channel tests presented above indicate that it is feasible to extract 0.05 g/min from a single microchannel, while maintaining an inlet concentration of 57% and outlet concentration of 60%. Thus, if scaling were linear, 4 g/min of refrigerant would require 80 parallel channels, each with a diameter of 0.127 mm. If the channels were arranged in a single array they would necessitate a device 2 cm x 2 cm and 2 mm thick. The separation chamber would add another 5 cm to the length, width and height, letting an entire desorber fit into a 5 cm x 5 cm x 7 cm volume. This desorber would also require a pump capable of providing about 70kPa continuously. Alternately, an array of 100 0.254 mm channels could provide the same desorption capacity, requiring 4 cm x 2 cm x 2 mm desorber and the same separation chamber as

needed for the previous example. This larger diameter system could also occupy a volume of 5 cm x 5 cm x 7 cm, but require only 7 kPa from a pump. In the model described, the largest component is the separation chamber, which could also be theoretically decreased in size with additional research. However, this result is based on each channel working independently. Interactions between droplet sprays are almost certain to interfere with desorption in a real system. If, for example, spray interactions decreased the system desorption by 25%, a 125 channel 5 cm x 2 cm x 2 mm desorber would be necessary, with almost no additional volume to the system due to the unchanged separation chamber size.

9. Conclusion and Recommendations

Single and multiple microchannel LiBr-water desorbers were tested under conditions similar to those required for heat pump operation. Tests were done at atmospheric pressure and involved boiling the solution as it passed through the channel and expelling it into a separation chamber, where the vapor was condensed for measurement. Tests with these two systems allow for the following conclusions:

1) Though lithium bromide complicates materials selection, combinations of metals and polymers can be used successfully in microchannel desorption systems. Titanium and Inconel are capable of withstanding concentrated solutions for limited periods of time, especially if there is little oxygen in the environment. Further, Teflon and PEEK can provide sufficient temperature and chemical resistance provided the pressures are not extreme.

2) Microchannel desorption can produce sufficient vapor quantities for cooling applications. A single microchannel with a diameter of 0.127 mm can produce 0.05 g/min of water vapor under the proper conditions. However, pressure requirements make such a desorber impractical in large-scale applications. But in situations where space is a constraint, a microchannel desorber can perform the same function as a falling film desorber in less than one fortieth of the volume, with 0.254 mm channels and a pump pressure requirement of 7 kPa.

3) Parallel microchannel desorbers, especially those with multiple reservoirs, are unstable under high heat fluxes, creating hotspots, and increasing both pressure requirement, and the possibility of crystallization. Uneven flow through the

channel array limits the utility of current systems to below their theoretical utility.

Also, the manufacturing technique used cannot reliably produce channels of sufficient length for necessary heat transfer area.

Further tests are recommended, focusing on the following areas:

1) A desorber at atmospheric pressure is easier to test and study, but has little practical application. A working desorber would need to consistently operate at sub-atmospheric conditions. While the partial vacuum would increase the system complexity, it would allow for the use of corrosion inhibitors, and low oxygen conditions. Thus a larger range of materials would be available for use. However, the passivation layer formed by the corrosion inhibitors would have to be examined to ensure that it would not obstruct the channels.

2) As mentioned repeatedly above, the multichannel array tested here was highly unstable, making useful comparisons to single channel flow nearly impossible. A functional desorber would need an even distribution of solution through all channels of the array, through careful design and manufacture. Stability could be increased by using a single microchannel array rather than a pair of arrays, but heat losses would be greater, and the heater would have to be capable of withstanding higher temperatures than the Kapton heaters tested here. The flow distribution could be further improved by implementing the system suggested by Kim et al. (2003), where the inlets of the individual channels project into the plenum, rather than being flush with the wall. While this innovation could make parallel arrays far more stable, it would greatly increase manufacturing complexity.

3) The manufacturing method must be modified to allow for longer channel lengths and closer tolerances. Current laser cutting technology and diffusion bonding can create complex and detailed components, but the process must be improved, or another manufacturing method must be identified for a functional desorber array.

4) The separation chamber is a simple device, using gravity to collect the solution at the bottom and the vapor at the top. However, the gravity operated device has several limitations. The first limitation is size. While the chamber is not large compared to a falling film desorber, it is the component that defines the volume for the microchannel desorber design examined here. Therefore, any improvements that decreased the size of the chamber without affecting its function could impart a corresponding decrease in size to the desorber. The second limitation is in the separation process. Under high heat flux conditions the solution exits the microchannels in a spray of droplets which rapidly cool. These droplets provide an ideal, high surface area, medium to reabsorb vapor that had been previously separated. In fact, a study by Ryan (1993) showed that such a spray is an excellent for applications where absorption of vapor is the goal, not a source of inefficiency. The third difficulty with a gravity separation chamber is that it is orientation dependant. While it will still operate at acute angles with little alteration, a portable system would be more useful if it were functional at any angle.

5) Finally, electrical heating is convenient for a laboratory setting, but not reasonable for portable use. If electric power is easily available then there is little reason to use an absorption-cycle heat pump. Therefore, a functional desorber must be

heated with either steam or combustion gases. Such a system is possible, using a standard cross-flow heat exchanger configuration, but would require further tests to establish reliability and performance. While a fuel powered system would not be as convenient for testing, it would be portable, and would solve the problem of damaging heater hotspots.

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Appendix A: Results Summary

Single Channel Results

Table A.1: Summary of single channel target values.

Target Values					
#	$D(mm)$	$x_{in}(\%)$	$\dot{Q}(W)$	$L(mm)$	$\dot{m}_{in}(g/min)$
1	0.127	47.0	5.00	25.0	0.600
2	0.127	47.0	6.00	25.0	0.700
3	0.127	47.0	7.00	25.0	0.800
4	0.127	52.0	5.00	25.0	0.600
5	0.127	52.0	6.00	25.0	0.700
6	0.127	52.0	7.00	25.0	0.800
7	0.127	57.0	5.00	25.0	0.700
8	0.127	57.0	6.00	25.0	0.800
9	0.127	57.0	7.00	25.0	0.600
10	0.254	47.0	5.00	25.0	0.800
11	0.254	47.0	6.00	25.0	0.600
12	0.254	47.0	7.00	25.0	0.700
13	0.254	52.0	5.00	25.0	0.700
14	0.254	52.0	6.00	25.0	0.800
15	0.254	52.0	7.00	25.0	0.600
16	0.254	57.0	5.00	25.0	0.800
17	0.254	57.0	6.00	25.0	0.600
18	0.254	57.0	7.00	25.0	0.700

D: Channel diameter

x_{in} : Concentration LiBr by mass

Q: Heat input

L: Channel Length

$\dot{m}_{in}$: Mass flow rate at inlet

Table A.2: Summary of single channel measured values.

Measured Values					
#	$D(mm)$	$x_{in}(\%)$	$\dot{Q}(W)$	$L(mm)$	$\dot{m}_{in}(g/min)$
1	0.127	46.2	4.98	25.0	0.598
2	0.127	46.2	5.96	25.0	0.698
3	0.127	46.3	7.04	25.0	0.795
4	0.127	52.3	4.98	25.0	0.599
5	0.127	52.3	5.96	25.0	0.702
6	0.127	52.3	7.04	25.0	0.805
7	0.127	57.1	4.98	25.0	0.702
8	0.127	56.9	5.96	25.0	0.798
9	0.127	56.9	7.04	25.0	0.603
10	0.254	46.9	4.98	25.0	0.799
11	0.254	46.9	5.96	25.0	0.602
12	0.254	46.9	7.04	25.0	0.702
13	0.254	51.7	4.98	25.0	0.697
14	0.254	51.8	5.96	25.0	0.801
15	0.254	51.7	7.04	25.0	0.595
16	0.254	56.6	4.98	25.0	0.795
17	0.254	56.6	5.96	25.0	0.601
18	0.254	56.7	7.04	25.0	0.698
$\pm$	0.005	0.1	0.05	0.1	0.002

D: Channel diameter

x_{in} : Concentration LiBr by mass, based on measured density (Lee et al. 1989)

Q: Heat input

L: Channel Length

$\dot{m}_{in}$: Mass flow rate at inlet

Table A.3: Summary of single channel test results.

Test Results					
#	$\dot{m}_{ref}$ (g/min)	x_{in} (%)	x_{out} (%)	x_{diff}	$\dot{Q}/\dot{m}_{ref}$ (W/(g/min))
1	0.053	46.2	50.7	4.5	94
2	0.056	46.2	50.3	4.0	106
3	0.065	46.3	50.4	4.1	108
4	0.040	52.3	56.0	3.7	125
5	0.056	52.3	56.8	4.5	106
6	0.054	52.3	56.0	3.8	130
7	0.025	57.1	59.2	2.1	199
8	0.044	56.9	60.2	3.3	135
9	0.035	56.9	60.4	3.5	201
10	0.046	46.9	49.7	2.9	108
11	0.036	46.9	49.9	3.0	166
12	0.054	46.9	50.8	3.9	130
13	0.040	51.7	54.9	3.1	125
14	0.052	51.8	55.4	3.6	115
15	0.038	51.7	55.2	3.5	185
16	0.030	56.6	58.9	2.2	166
17	0.024	56.6	59.0	2.4	248
18	0.042	56.7	60.3	3.6	168
±	0.002	0.1	0.2	0.2	3

$\dot{m}_{ref}$: Mass flow rate of condensed vapor

x_{in} : Concentration LiBr by mass at channel inlet, based on measured density (Lee et al. 1989)

x_{out} : Concentration LiBr by mass at chamber exit, based on species balance

x_{diff} : Difference between concentration at inlet and exit

$\dot{Q}/\dot{m}_{ref}$: Heat per unit condensed vapor

Table A.4: Summary of single channel test conditions.

Test Conditions						
#	$\rho_{flow} (kg/m^3)$	$T_{flow} (^{\circ}C)$	$T_{pre} (^{\circ}C)$	$T_{in} (^{\circ}C)$	$T_{sep} (^{\circ}C)$	$T_{sat} (^{\circ}C)$
1	1474	24	115	88	68	132
2	1474	24	111	88	70	133
3	1475	24	110	90	71	134
4	1572	24	119	98	78	146
5	1572	24	121	101	76	147
6	1572	24	120	102	96	148
7	1662	26	121	100	92	161
8	1659	24	129	106	88	161
9	1659	24	127	113	100	157
10	1483	25	109	95	70	126
11	1484	25	110	97	75	126
12	1483	25	109	104	86	126
13	1562	25	110	91*	74	136
14	1563	25	109	91*	75	136
15	1562	25	107	91*	93	136
16	1654	25	122	102*	82	147
17	1654	25	122	102*	85	147
18	1654	26	120	102*	106	147
$\pm$	1	1	1	1	1	

ρ_{flow} : Solution density measured by flow meter

T_{flow} : Temperature measured by flow meter

T_{pre} : Measured temperature in preheater

T_{in} : Measured temperature at channel inlet

T_{sep} : Measured temperature in separation chamber

T_{sat} : Calculated saturation temperature (McNeely, 1979)

*: Estimated values, based on similar conditions of other tests. Thermocouple failed.

Table A.5: Summary of single channel thermodynamic model.

Thermodynamic Model						
#	$\dot{Q}_{in}(W)$	$\dot{Q}_{ref}(W)$	$\dot{Q}_{out}(W)$	$\dot{Q}_{total}(W)$	$\dot{Q}_{lost}(W)$	$\eta(\%)$
1	1.89	2.37	2.93	3.41	1.57	68.4
2	2.21	2.50	3.46	3.75	2.21	63.0
3	2.57	2.91	3.93	4.26	2.78	60.5
4	2.10	1.79	2.99	2.68	2.30	53.7
5	2.54	2.50	3.46	3.43	2.53	57.5
6	2.94	2.42	4.02	3.49	3.55	49.6
7	2.60	1.12	3.66	2.18	2.80	43.7
8	3.11	1.97	4.10	2.96	3.00	49.7
9	2.50	1.57	3.10	2.17	4.87	30.8
10	2.73	2.06	4.07	3.39	1.59	68.1
11	2.10	1.61	3.05	2.56	3.40	42.9
12	2.64	2.42	3.48	3.25	3.79	46.2
13	2.27	1.79	3.51	3.03	1.95	60.8
14	2.60	2.33	4.00	3.72	2.24	62.4
15	1.93	1.70	2.97	2.74	4.30	38.9
16	2.99	1.34	4.13	2.49	2.49	49.9
17	2.26	1.07	3.12	1.93	4.03	32.4
18	2.63	1.88	3.58	2.83	4.21	40.2
$\pm$	0.01	0.01	0.02	0.01	0.03	0.5

Q_{in} : Calculated enthalpy of solution at channel entrance (McNeely, 1979)

Q_{ref} : Calculated enthalpy of water vapor (Çengel and Boles, 1998)

Q_{out} : Calculated enthalpy of solution at exit (McNeely, 1979)

Q_{total} : Difference in entrance and exit enthalpy

Q_{lost} : Difference between Q_{total} and Q

η : Calculated desorption efficiency based on Q and Q_{lost}

Table A.6: Summary of single channel solution properties.

Solution Properties						
#	ρ_{flow}	ρ_{in}	ρ_{sat}	μ_{flow}	μ_{in}	μ_{sat}
1	1474	1441	1328	2.01E-3	1.04E-3	7.05E-4
2	1474	1441	1326	2.01E-3	1.04E-3	7.00E-4
3	1475	1441	1326	2.02E-3	1.02E-3	6.97E-4
4	1572	1528	1393	2.86E-3	1.30E-3	8.56E-4
5	1572	1526	1391	2.86E-3	1.26E-3	8.49E-4
6	1572	1526	1390	2.86E-3	1.24E-3	8.42E-4
7	1662	1614	1456	4.12E-3	1.72E-3	9.97E-4
8	1659	1606	1452	4.05E-3	1.59E-3	9.84E-4
9	1659	1602	1457	4.05E-3	1.48E-3	1.01E-3
10	1483	1446	1343	2.08E-3	9.94E-4	7.57E-4
11	1484	1446	1344	2.08E-3	9.78E-4	7.59E-4
12	1483	1441	1343	2.08E-3	9.11E-4	7.57E-4
13	1562	1523	1397	2.76E-3	1.36E-3	8.93E-4
14	1563	1524	1398	2.77E-3	1.36E-3	8.94E-4
15	1562	1523	1398	2.76E-3	1.36E-3	8.94E-4
16	1654	1605	1466	3.98E-3	1.64E-3	1.07E-3
17	1654	1605	1467	3.98E-3	1.64E-3	1.07E-3
18	1654	1605	1467	3.99E-3	1.64E-3	1.08E-3
$\pm$	1	1	1	3.78E-6	1.33E-6	7.61E-7

ρ_{flow} : Density measured by flow meter

ρ_{in} : Density calculated for inlet temperature (Lee et al. 1989)

ρ_{sat} : Density calculated for saturation (Lee et al. 1989)

μ_{flow} : Viscosity calculated for flow meter temperature (Lee et al. 1989)

μ_{in} : Viscosity calculated for inlet temperature (Lee et al. 1989)

μ_{sat} : Viscosity calculated for saturation temperature (Lee et al. 1989)

Table A.7: Summary of single channel flow conditions.

Flow Conditions						
#	$V_{flow} (m/s)$	$V_{in} (m/s)$	$V_{sat} (m/s)$	Re_{flow}	Re_{in}	Re_{sat}
1	0.534	0.546	0.593	49.7	96.4	141.8
2	0.623	0.637	0.692	58.0	112.5	166.7
3	0.709	0.725	0.789	65.8	130.5	190.6
4	0.501	0.516	0.566	35.0	77.2	116.9
5	0.587	0.605	0.663	41.0	93.3	138.1
6	0.674	0.694	0.762	47.0	108.2	159.8
7	0.556	0.572	0.634	28.5	68.1	117.7
8	0.633	0.653	0.723	32.9	83.9	135.4
9	0.478	0.495	0.544	24.9	68.2	99.7
10	0.177	0.182	0.196	32.2	67.1	88.2
11	0.133	0.137	0.147	24.2	51.5	66.3
12	0.156	0.160	0.172	28.3	64.4	77.4
13	0.147	0.151	0.164	21.1	43.0	65.2
14	0.169	0.173	0.188	24.1	49.2	74.8
15	0.125	0.128	0.140	18.0	36.7	55.6
16	0.158	0.163	0.178	16.7	40.6	61.9
17	0.120	0.123	0.135	12.6	30.7	46.7
18	0.139	0.143	0.157	14.6	35.6	54.3
±	0.010	0.010	0.012	0.6	1.4	2.4

V_{flow} : Channel velocity calculated for temperature at flow meter

V_{in} : Channel velocity calculated for temperature at inlet

V_{sat} : Channel velocity calculated for saturation temperature

Re_{flow} : Reynolds number for V_{flow}

Re_{in} : Reynolds number for V_{in}

Re_{sat} : Reynolds number for V_{sat}

Table A.8: Summary of single channel pressure measurements.

Pressures (kPa)						
#	P_{flow}	P_{in}	P_{sat}	P	<i>Deviation</i>	%
1	53.26	28.07	20.73	22.41	0.06	0.25
2	62.14	32.74	24.02	25.86	0.06	0.24
3	70.95	36.62	27.24	34.48	0.09	0.26
4	71.17	33.17	24.02	24.69	0.27	1.09
5	83.37	37.71	27.95	27.59	0.10	0.38
6	95.67	42.85	31.83	49.66	0.22	0.44
7	113.55	48.81	31.34	68.21	0.21	0.30
8	127.03	51.46	35.27	37.45	0.21	0.55
9	96.01	36.25	27.26	47.93	1.74	3.64
±	8.08	2.86	2.24	0.41		
10	4.56	2.24	1.84	1.66	0.03	1.67
11	3.45	1.66	1.39	4.21	0.01	0.33
12	4.01	1.81	1.61	6.48	0.01	0.21
13	5.03	2.53	1.82	1.38	0.02	1.50
14	5.79	2.91	2.09	1.66	0.01	0.83
15	4.29	2.16	1.55	4.62	0.02	0.45
16	7.80	3.30	2.37	2.28	0.07	3.03
17	5.89	2.50	1.80	3.45	0.06	1.60
18	6.87	2.91	2.09	5.31	0.07	1.30
±	1.61	0.67	0.49	0.41		

P_{flow} : Estimate of pressure drop based on T_{flow} (single phase, laminar)

P_{in} : Estimate of pressure drop based on T_{in} (single phase, laminar)

P_{sat} : Estimate of pressure drop based on T_{sat} (single phase, laminar)

P : Average pressure measured by pressure transducer over 1 minute

Deviation: Standard deviation of pressure measurements over one minute

%: Deviation divided by average pressure

Multi-Channel Results

Table A.9: Summary of multi-channel target values.

Target Values					
#	$D(mm)$	$x_{in}(\%)$	$\dot{Q}(W)$	$L(mm)$	$\dot{m}_{in}(g/min)$
1	0.127	47.0	22.00	8.5	7.00
2	0.127	47.0	25.00	8.5	7.00
3	0.127	47.0	28.00	8.5	7.00
4	0.127	52.0	22.00	8.5	7.00
5	0.127	52.0	25.00	8.5	7.00
6	0.127	52.0	28.00	8.5	7.00
7	0.127	57.0	22.00	8.5	7.00
8	0.127	57.0	25.00	8.5	7.00
9	0.127	57.0	28.00	8.5	7.00

D: Channel hydraulic diameter

x_{in} : Concentration LiBr by mass

Q: Heat input

L: Channel Length

$\dot{m}_{in}$: Mass flow rate at inlet

Table A.10: Summary of multi-channel measured values.

Measured Values					
#	$D(mm)$	$x_{in}(\%)$	$\dot{Q}(W)$	$L(mm)$	$\dot{m}_{in}(g/min)$
1	0.127	47.6	21.92	8.5	7.10
2	0.127	47.0	24.92	8.5	7.08
3	0.127	47.4	27.92	8.5	6.90
4	0.127	52.2	21.92	8.5	7.20
5	0.127	52.0	24.92	8.5	7.13
6	0.127	52.4	27.92	8.5	7.10
7	0.127	57.2	21.92	8.5	6.98
8			Unstable		
9			Unstable		
$\pm$	0.005	0.1	0.05	0.1	0.11

D: Channel diameter

x_{in} : Concentration LiBr by mass, based on measured density (Lee et al. 1989)

Q: Heat input

L: Channel Length

$\dot{m}_{in}$: Measured mass flow rate at inlet

Table A.11: Summary of multi-channel test results.

Test Results					
#	$\dot{m}_{ref}$ (g/min)	x_{in} (%)	x_{out} (%)	x_{diff}	$\dot{Q}/\dot{m}_{ref}$ (W/(g/min))
1	0.092	47.6	48.3	0.6	237
2	0.109	47.0	47.7	0.7	228
3	0.169	47.4	48.6	1.2	165
4	0.099	52.2	52.9	0.7	221
5	0.107	52.0	52.7	0.8	232
6	0.142	52.4	53.4	1.1	196
7	0.082	57.2	57.9	0.7	267
8					
9					
$\pm$	0.006	0.1	0.2	0.2	6

$\dot{m}_{ref}$: Mass flow rate of condensed vapor

x_{in} : Concentration LiBr by mass at channel inlet, based on measured density (Lee et al. 1989)

x_{out} : Concentration LiBr by mass at chamber exit, based on species balance

x_{diff} : Difference between concentration at inlet and exit

$\dot{Q}/\dot{m}_{ref}$: Heat per unit condensed vapor

Table A.12: Summary of multi-channel test conditions.

Test Conditions					
#	$\rho_{flow} (kg/m^3)$	$T_{flow} (^\circ C)$	$T_{in} (^\circ C)$	$T_{sep} (^\circ C)$	$T_{sat} (^\circ C)_{est}$
1	1493	28	65	67	139
2	1483	28	65	76	138
3	1490	28	65	80	138
4	1569	28	66	58	151
5	1564	29	66	68	150
6	1572	28	68	71	151
7	1662	29	74	56	165
8					
9					
$\pm$	1	1	1	1	

ρ_{flow} : Solution density measured by flow meter

T_{flow} : Temperature measured by flow meter

T_{in} : Measured temperature at channel inlet

T_{sep} : Measured temperature in separation chamber

T_{sat} : Calculated saturation temperature (McNeely, 1979)

Table A.13: Summary of multi-channel thermodynamic model.

Thermodynamic Model						
#	$\dot{Q}_{in}(W)$	$\dot{Q}_{ref}(W)$	$\dot{Q}_{out}(W)$	$\dot{Q}_{total}(W)$	$\dot{Q}_{lost}(W)$	$\eta(\%)$
1	16.1	4.1	35.6	23.6	-1.6	107
2	16.1	4.9	35.1	23.8	1.1	96
3	15.7	7.6	33.8	25.7	2.2	92
4	17.0	4.4	38.5	26.0	-4.0	118
5	16.8	4.8	37.9	25.9	-1.0	104
6	17.3	6.4	37.7	26.8	1.2	96
7	19.8	3.7	40.7	24.6	-2.6	112
8						
9						
$\pm$	0.33	0.08	0.2	0.1	0.1	1

Q_{in} : Calculated enthalpy of solution at channel entrance (McNeely, 1979)

Q_{ref} : Calculated enthalpy of water vapor (Çengel and Boles, 1998)

Q_{out} : Calculated enthalpy of solution at exit (McNeely, 1979)

Q_{total} : Difference in entrance and exit enthalpy

Q_{lost} : Difference between Q_{total} and Q

η : Calculated desorption efficiency based on Q and Q_{lost}

Table A.14: Summary of multi-channel solution properties.

Solution Properties						
#	ρ_{flow}	ρ_{in}	ρ_{sat}	μ_{flow}	μ_{in}	μ_{sat}
1	1493	1474	1336	2.16E-3	1.47E-3	7.15E-4
2	1483	1464	1330	2.09E-3	1.42E-3	7.02E-4
3	1490	1471	1335	2.14E-3	1.46E-3	7.13E-4
4	1569	1547	1385	2.85E-3	1.91E-3	8.21E-4
5	1564	1543	1382	2.81E-3	1.88E-3	8.16E-4
6	1572	1549	1387	2.89E-3	1.87E-3	8.29E-4
7	1662	1634	1452	4.15E-3	2.40E-3	9.72E-4
8						
9						
$\pm$	1	1	1	4E-6	2E-6	6E-7

ρ_{flow} : Density measured by flow meter

ρ_{in} : Density calculated for inlet temperature (Lee et al. 1989)

ρ_{sat} : Density calculated for saturation (Lee et al. 1989)

μ_{flow} : Viscosity calculated for flow meter temperature (Lee et al. 1989)

μ_{in} : Viscosity calculated for inlet temperature (Lee et al. 1989)

μ_{sat} : Viscosity calculated for saturation temperature (Lee et al. 1989)

Table A.15: Summary of multi-channel flow conditions.

Flow Conditions						
#	$V_{flow} (m/s)$	$V_{in} (m/s)$	$V_{sat} (m/s)$	Re_{flow}	Re_{in}	Re_{sat}
1	0.626	0.634	0.699	56	81	166
2	0.628	0.636	0.700	57	83	169
3	0.609	0.617	0.680	54	79	162
4	0.604	0.613	0.685	42	63	147
5	0.600	0.608	0.679	42	64	146
6	0.594	0.603	0.673	41	63	143
7	0.553	0.562	0.632	28	49	120
8						
9						
$\pm$	0.127	0.129	0.145	6	11	28

V_{flow} : Channel velocity calculated for temperature at flow meter

V_{in} : Channel velocity calculated for temperature at inlet

V_{sat} : Channel velocity calculated for saturation temperature

Re_{flow} : Reynolds number for V_{flow}

Re_{in} : Reynolds number for V_{in}

Re_{sat} : Reynolds number for V_{sat}

Table A.16: Summary of multi-channel pressure measurements.

Pressures (kPa)						
#	$P_{flow\ est}$	$P_{in\ est}$	$P_{sat\ est}$	P	<i>Deviation</i>	%
1	9.72	6.71	3.60	3.16	0.06	1.9
2	9.42	6.51	3.54	2.99	0.04	1.3
3	9.36	6.46	3.49	2.79	0.10	3.8
4	12.4	8.40	4.04	3.50	0.09	2.6
5	12.1	8.20	3.98	3.41	0.04	1.2
6	12.3	8.13	4.01	3.78	0.15	4.0
7	16.5	9.71	4.42	4.12	0.18	4.4
8						
9						
$\pm$	3.37	7.53	3.36	0.04		

P_{flow} : Estimate of pressure drop based on T_{flow} (single phase, laminar)

P_{in} : Estimate of pressure drop based on T_{in} (single phase, laminar)

P_{sat} : Estimate of pressure drop based on T_{sat} (single phase, laminar)

P : Average pressure measured by pressure transducer over 1 minute

Deviation: Standard deviation of pressure measurements over one minute

%: Deviation divided by average pressure

Single Channel, High Flow Rate Results

Table A.17: Summary of single channel, high flow rate target values.

Target Values					
#	$D(mm)$	$x_{in}(\%)$	$\dot{Q}(W)$	$L(mm)$	$\dot{m}_{in}(g/min)$
1	0.254	52.0	14.0	25.0	2.80
2	0.254	52.0	18.0	25.0	2.80
3	0.254	52.0	20.0	25.0	2.80

D: Channel diameter

x_{in} : Concentration LiBr by mass

Q: Heat input

L: Channel Length

$\dot{m}_{in}$: Mass flow rate at inlet

Table A.18: Summary of single channel, high flow rate measured values.

Measured Values					
#	$D(mm)$	$x_{in}(\%)$	$\dot{Q}(W)$	$L(mm)$	$\dot{m}_{in}(g/min)$
1	0.254	52.1	13.98	25.0	2.80
2	0.254	52.4	17.95	25.0	2.80
3	0.254	52.0	20.05	25.0	2.79
$\pm$	0.005	0.1	0.05	0.1	0.002

D: Channel diameter

x_{in} : Concentration LiBr by mass, based on measured density (Lee et al. 1989)

Q: Heat input

L: Channel Length

$\dot{m}_{in}$: Mass flow rate at inlet

Table A.19: Summary of single channel, high flow rate test results.

Test Results					
#	$\dot{m}_{ref} (g/min)$	$x_{in} (\%)$	$x_{out} (\%)$	x_{diff}	$\dot{Q}/\dot{m}_{ref} (W/(g/min))$
1	0.116	52.4	54.7	2.3	120
2	0.163	52.1	55.3	3.2	110
3	0.188	52.0	55.8	3.8	107
$\pm$	0.002	0.1	0.2	0.2	3

$\dot{m}_{ref}$: Mass flow rate of condensed vapor

x_{in} : Concentration LiBr by mass at channel inlet, based on measured density (Lee et al. 1989)

x_{out} : Concentration LiBr by mass at chamber exit, based on species balance

x_{diff} : Difference between concentration at inlet and exit

$\dot{Q}/\dot{m}_{ref}$: Heat per unit condensed vapor

Table A.20: Summary of single channel, high flow rate test conditions.

Test Conditions						
#	$\rho_{flow} (kg/m^3)$	$T_{flow} (^\circ C)$	$T_{pre} (^\circ C)$	$T_{in} (^\circ C)$	$T_{sep} (^\circ C)$	$T_{sat} (^\circ C)$
1	1574	25	108	102	110	140
2	1569	25	109	107	119	139
3	1567	25	110	122	130	138
$\pm$	1	1	1	1	1	

ρ_{flow} : Solution density measured by flow meter

T_{flow} : Temperature measured by flow meter

T_{pre} : Measured temperature in preheater

T_{in} : Measured temperature at channel inlet

T_{sep} : Measured temperature in separation chamber

T_{sat} : Calculated saturation temperature (McNeely, 1979)

Appendix B: Uncertainty and Calibration

Included is a sample calibration and uncertainty calculation performed for the low range pressure transducer used in 0.254 mm single channel tests. Similar calibration was performed for the high range pressure transducer, Coriolis flow meter, thermocouples, and conductivity meter. Measured and manufacturer supplied uncertainties were propagated using partial derivatives and the Root Sum Square method.

Procedure

A Dwyer series 477 Digital Manometer was used as a low pressure standard, with a manufacturer supplied uncertainty of 0.05 psi for the range from 0 - 10 psi. Air pressure was supplied to both the transducer and the and the manometer simultaneously and the voltage output by the transducer was recorded using LabVIEW. After balancing the voltage output to best use the full available voltage range for the pressures desired, voltages were recorded for 24 air pressure levels, with five repetitions at each pressure. The average values for the five repetitions were matched to a Least Sum Squares model in Microsoft Excel. The difference between that model and each measured point was averaged as an average fit error. The standard deviation of the individual fit errors was multiplied by 2.086, the t-value based on the number of degrees of freedom. The total fit error was calculated by combining the average fit error and the deviation error with the Root Sum Squares

method. Finally, the measurement error was calculated based on the calibration fit error and the manometer uncertainty.

Calibration

Table B.1: Results of low pressure transducer calibration.

$P_{measured}$	V	P_{calc}	$Diff$
0	0.505	0.082	0.082
0.25	0.602	0.235	0.015
0.42	0.697	0.384	0.036
0.68	0.888	0.683	0.003
0.89	1.017	0.886	0.004
1.22	1.223	1.209	0.011
1.44	1.364	1.430	0.01
1.71	1.534	1.697	0.013
2.1	1.810	2.129	0.029
2.59	2.099	2.583	0.007
2.99	2.351	2.979	0.011
3.37	2.597	3.365	0.005
3.87	2.914	3.862	0.008
4.52	3.325	4.506	0.014
4.88	3.560	4.875	0.004
5.53	3.979	5.533	0.003
6.06	4.318	6.065	0.005
6.59	4.649	6.58	0.006
6.97	4.889	6.960	0.009
7.34	5.144	7.360	0.020
7.68	5.345	7.676	0.004
8.24	5.705	8.241	0.001
8.61	5.947	8.620	0.010
9.35	6.413	9.352	0.002
		average	0.013
		Std dev	0.017
		T	2.086
		calibrate	0.038
		Total	0.062

For the range from 0 to 9.35 psi, the calculated uncertainty, based on the curve fit and the measurement standard was 0.06 psi. While the measurement standard

provides the largest portion of the uncertainty, both are on the same order. Therefore, neither improving the measurement standard nor the instrument alone would greatly increase the accuracy of this pressure data. For 0.127 mm single channel tests, this uncertainty was reasonable, as the pressure was usually in the 3 to 10 psi range. However, for the 0.254 mm channel, uncertainty was as high as 29%.

Appendix C: Pressure Response

The following figures show the pressure distribution measured for each of the single channel and multi-channel desorption tests. All measurements were taken with a diaphragm-type pressure transducer, with an uncertainty of 0.4 kPa. The periodic, sinusoidal flow pattern visible in the single channel tests was caused by variation in the pressure from the syringe pumps.

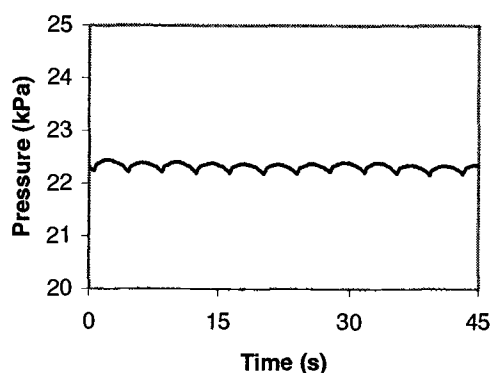


Figure C.1: Pressure response over 45 seconds at 100 Hz, single 0.127 mm channel, 4.98 W, 0.598 g/min, 46.2 % LiBr.

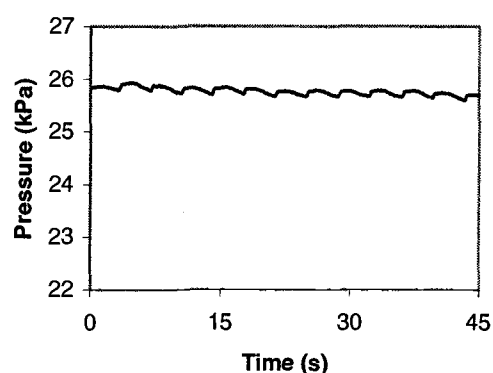


Figure C.2: Pressure response over 45 seconds at 100 Hz, single 0.127 mm channel, 5.96 W, 0.698 g/min, 46.2 % LiBr.

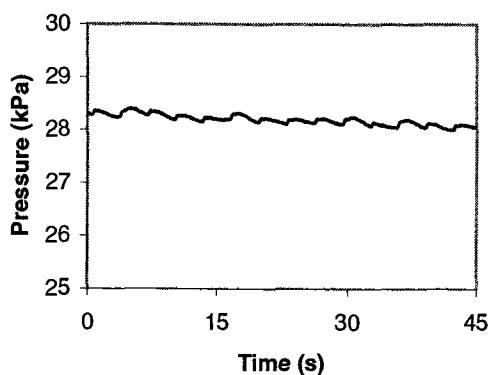


Figure C.3: Pressure response over 45 seconds at 100 Hz, single 0.127 mm channel, 7.04 W, 0.795 g/min, 46.3 % LiBr.

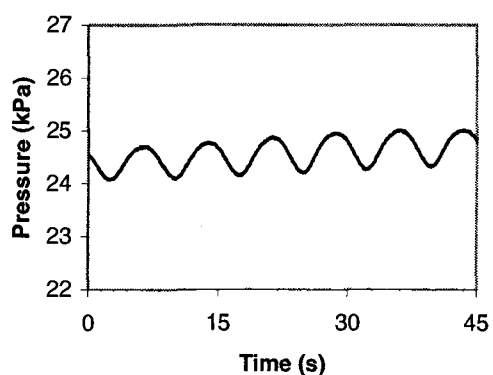


Figure C.4: Pressure response over 45 seconds at 100 Hz, single 0.127 mm channel, 4.98 W, 0.599 g/min, 52.3 % LiBr.

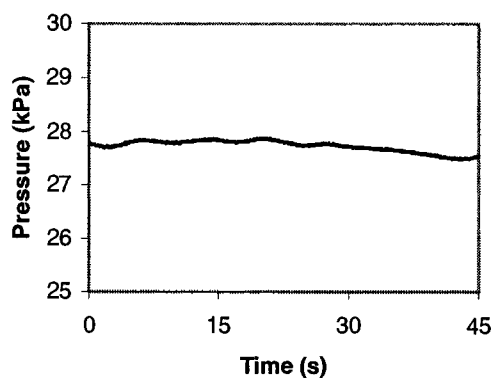


Figure C.5: Pressure response over 45 seconds at 100 Hz, single 0.127 mm channel, 5.96 W, 0.702 g/min, 52.3 % LiBr.

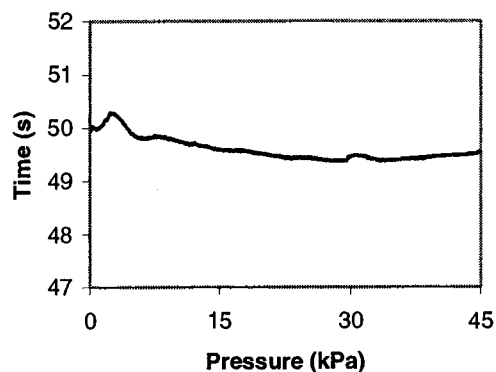


Figure C.6: Pressure response over 45 seconds at 100 Hz, single 0.127 mm channel, 7.04 W, 0.805 g/min, 52.3% LiBr.

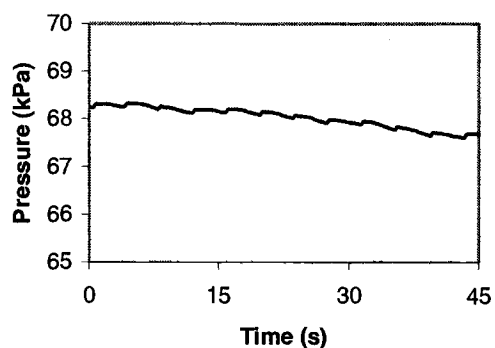


Figure C.7: Pressure response over 45 seconds at 100 Hz, single 0.127 mm channel, 4.98 W, 0.702 g/min, 57.1 % LiBr.

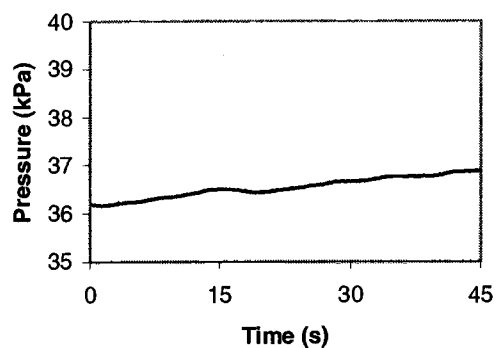


Figure C.8: Pressure response over 45 seconds at 100 Hz, single 0.127 mm channel, 5.96 W, 0.798 g/min, 56.9% LiBr.

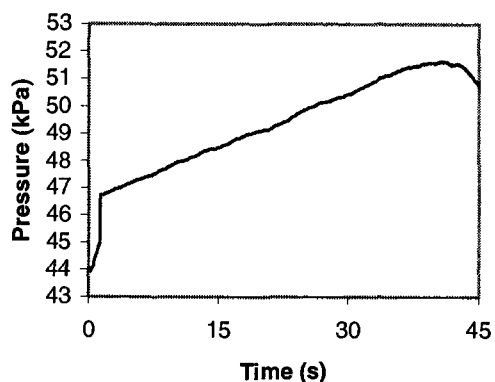


Figure C.9: Pressure response over 45 seconds at 100 Hz, single 0.127 mm channel, 7.04 W, 0.603 g/min, 56.9 % LiBr.

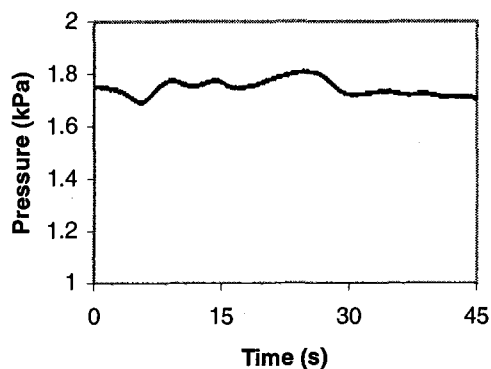


Figure C.10: Pressure response over 45 seconds at 100 Hz, single 0.254 mm channel, 4.98 W, 0.799 g/min, 46.9 % LiBr.

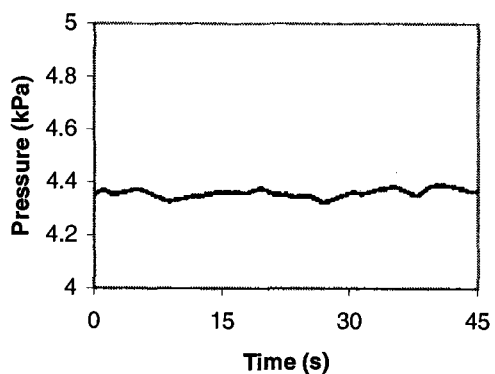


Figure C.11: Pressure response over 45 seconds at 100 Hz, single 0.254 mm channel, 5.96 W, 0.602 g/min, 46.9 % LiBr.

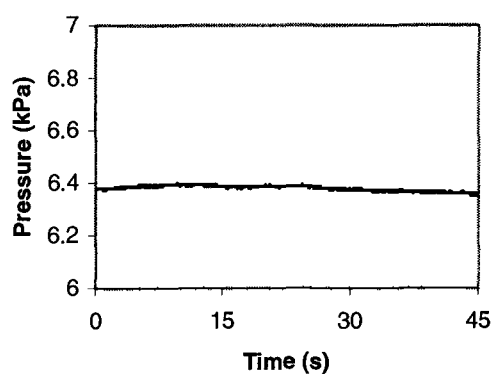


Figure C.12: Pressure response over 45 seconds at 100 Hz, single 0.254 mm channel, 7.04 W, 0.702 g/min, 46.9 % LiBr.

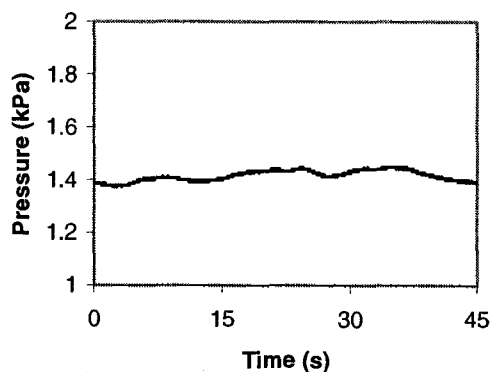


Figure C.13: Pressure response over 45 seconds at 100 Hz, single 0.254 mm channel, 4.98 W, 0.697 g/min, 51.7 % LiBr.

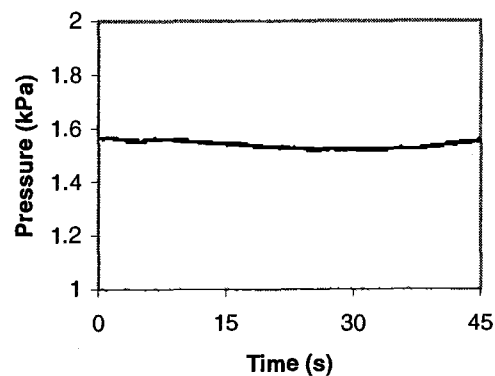


Figure C.14: Pressure response over 45 seconds at 100 Hz, single 0.254 mm channel, 5.96 W, 0.801 g/min, 51.8 % LiBr.

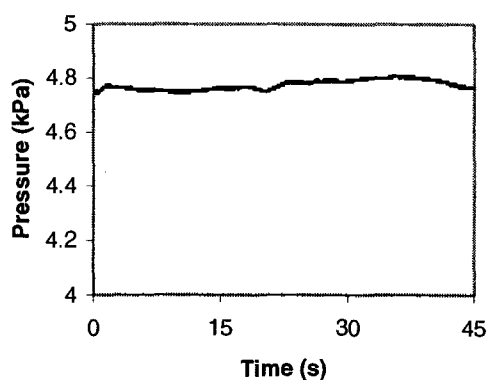


Figure C.15: Pressure response over 45 seconds at 100 Hz, single 0.254 mm channel, 7.04 W, 0.595 g/min, 51.7 % LiBr.

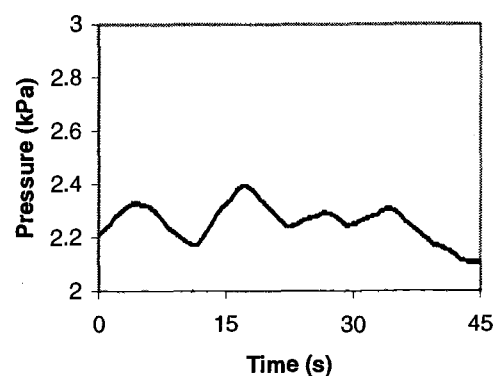


Figure C.16: Pressure response over 45 seconds at 100 Hz, single 0.254 mm channel, 4.98 W, 0.795 g/min, 56.6 % LiBr.

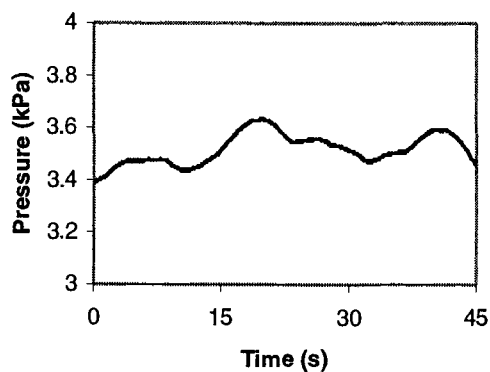


Figure C.17: Pressure response over 45 seconds at 100 Hz, single 0.254 mm channel, 5.96 W, 0.601 g/min, 56.6% LiBr.

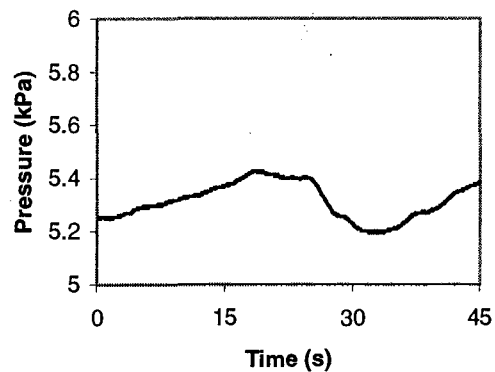


Figure C.18: Pressure response over 45 seconds at 100 Hz, single 0.254 mm channel, 7.04 W, 0.698 g/min, 56.7% LiBr.

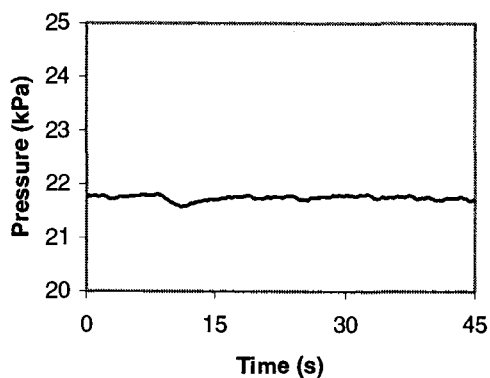


Figure C.19: Pressure response over 45 seconds at 100 Hz, 0.133 mm channel array, 21.92 W, 7.10 g/min, 47.6% LiBr.

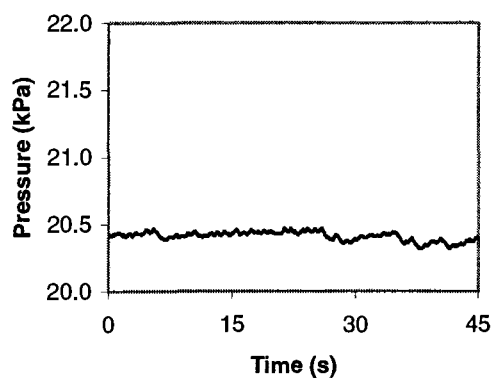


Figure C.20: Pressure response over 45 seconds at 100 Hz, 0.133 mm channel array, 24.92 W, 7.08 g/min, 47.0% LiBr.

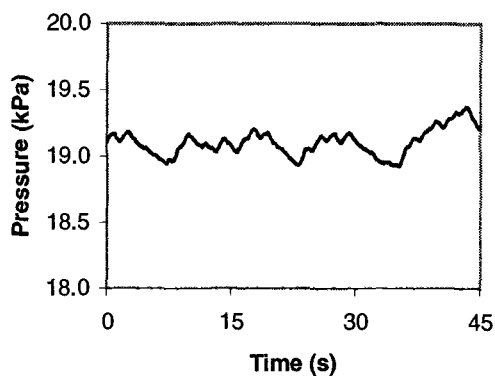


Figure C.21: Pressure response over 45 seconds at 100 Hz, 0.133 mm channel array, 27.92 W, 6.90 g/min, 47.4% LiBr.

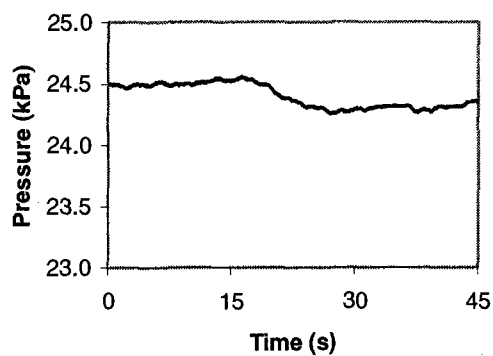


Figure C.22: Pressure response over 45 seconds at 100 Hz, 0.133 mm channel array, 21.92 W, 7.20 g/min, 52.2% LiBr.

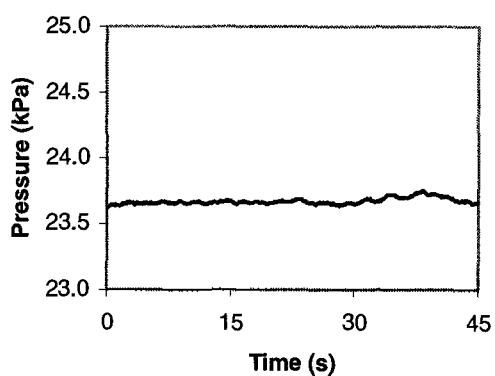


Figure C.23: Pressure response over 45 seconds at 100 Hz, 0.133 mm channel array, 24.92 W, 7.13 g/min, 52.0% LiBr.

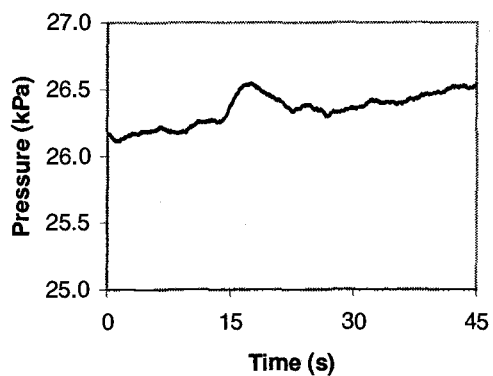


Figure C.24: Pressure response over 45 seconds at 100 Hz, 0.133 mm channel array, 27.92 W, 7.10 g/min, 52.4% LiBr.

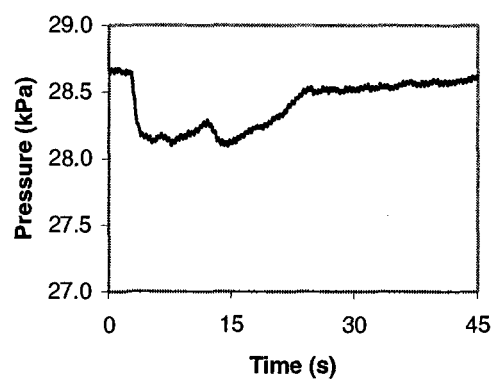


Figure C.25: Pressure response over 45 seconds at 100 Hz, 0.133 mm channel array, 21.92 W, 6.98 g/min, 57.2% LiBr..

Appendix D: Design Chronology

Desorber Designs

Preliminary desorption tests were performed with a series of desorbers and separation chambers, each designed to improve on the weaknesses of the previous. Following is a chronology of desorption research, cataloging development toward a functional prototype.

Separation chamber

The separation chamber allows for the vapor produced in the microchannels to be gathered and used. All designs here use differences in buoyancy between vapor and solution to collect the refrigerant at the top and the Lithium Bromide-water at the bottom.

Separation Chamber #1

The first separation chamber design, shown in Figure D.1, focused on the feasibility of gravity separation, and the ability to visualize the process. A cavity was hollowed out of a Teflon block with access from five directions. Teflon was used for most of the functional components of the separation chamber because it is easily machinable, resistant to corrosion, thermally insulative, relatively inexpensive, and capable of withstanding high temperatures. The microchannel and its heating device were pressed into a 1 inch Teflon plug, sealing the channel exit to the chamber

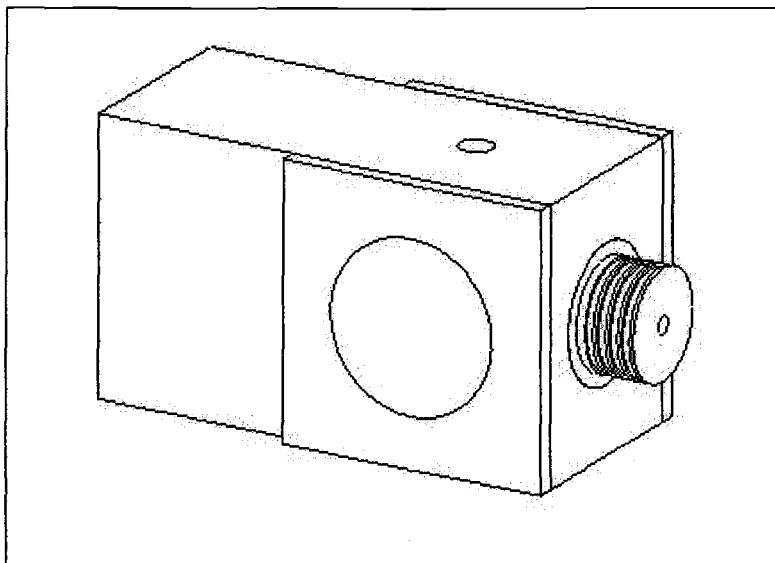


Figure D.1: Representation of separation chamber #1.

entrance. Heated LiBr-water solution was pumped through the microchannel by paired syringe pumps, began boiling within the confined space, then was expelled into the separation chamber. Vapor was allowed to escape from upper access point, while concentrated solution was collected at the lower. Two large Calcium Fluoride windows allowed for both visual observation and infrared images of the process within the chamber.

Testing with this separation chamber proved that water could be separated from LiBr-water solution using microchannel boiling. At high heat fluxes a spray of droplets was visible exiting the channel, and vapor was observed escaping from the top. The spray varied based on flow rate and heat addition, transitioning from slow drips from the channel exit, to alternating drips with periodic jets, to a continuous jet of solution, to alternating jets and spray of mixed droplets and vapor, to continuous spray of droplets and vapor. Each transition produced a greater amount of vapor, and

corresponding greater increase in the exit solution concentration. However, vapor produced was inconsistent in amount, and well below the calculated magnitude, based on flow rate and heat flux. Too much of the generated vapor was condensing on the inner surfaces of the separation chamber, especially on the windows. Further, images of the chamber interior during operation proved to be of low quality. The spray of droplets exiting the channel soon covered all available inner surfaces, including the viewing windows. Further, the vapor condensing on the windows inhibited viewing and decreased the total vapor yield. To counter this condensation, transparent resistance heaters were placed on the outer surfaces of the windows. While the heaters did greatly enhance the view into the chamber, they were not of optical clarity. Therefore, accurate images, especially at the desired scale, were not possible. Also, the heated window made infrared images of the chamber contents useless, as the windows themselves then provided a heat source. With the windows as a heat source, a confounding variable was added to desorption calculations, as the microchannel was no longer the only heat source available for evaporation. For these reasons, favorable observational data was available, but little precise testing was possible using this separation system.

Separation Chamber #2

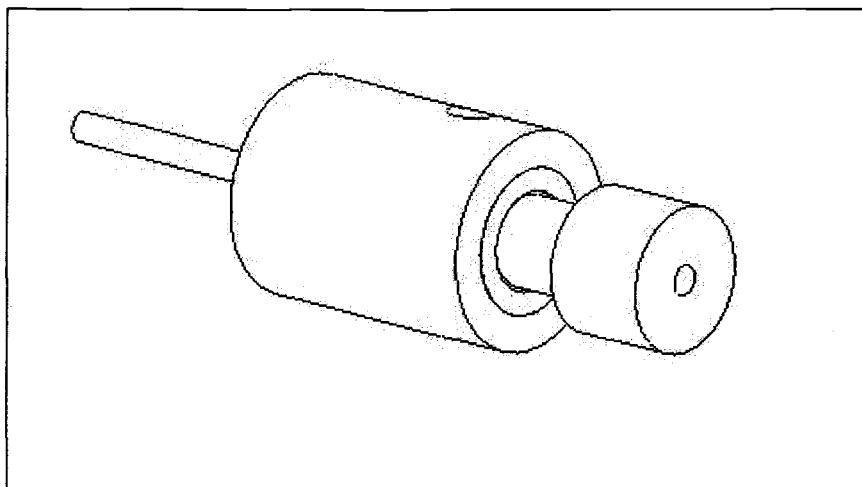


Figure D.2: Representation of separation chamber #2.

The second separation chamber design, shown in Figure D.2, was prepared to address some of the limitations of the first. This separation chamber was also manufactured of Teflon, but without the capacity for internal viewing. It was decided that the images were not of sufficient quality to study closely, and the heat losses were too excessive for accurate data. Therefore two separation chambers were designed, one system for accurate images, and another for accurate desorption data. Figure D.2 shows the design intended for practical desorption. This design does not include provisions for internal viewing, thereby reducing internal condensation, removing the unwanted heat source, and allowing for more complete insulation. The rear wall of the chamber was replaced by a variable piston, allowing for easy adjustment of the chamber length. Heat was again supplied electrically to LiBr-water solution as it

flowed through the microchannel, before being expelled into the chamber for separation.

Tests with separation chamber #2 showed excellent gains in vapor production. The increased insulation and shorter channel section allowed for water vapor to exit the chamber in measurable quantities. Preliminary attempts at gathering the vapor and measuring it were begun. However, two flaws in this design were soon apparent. First, the spray of droplets from the channel exit drifted and scattered in all directions, often sending droplets of LiBr-water solution out of the chamber and into the vapor stream. Second, the fiberglass batting used for insulation provided inconsistent heat transfer rates and absorbed much of the departing vapor. So, while the results were promising, the Lithium Bromide in the vapor measurements made gathered data useless.

Separation Chamber #3

The third separation chamber design, shown in Figure D.3, was prepared to counter the specific flaws of the second. As the chambers before it, it was manufactured of Teflon, and included a stainless steel, 2.5 cm long, electrically heated microchannel. The difference in this device was the orientation. Rather than a horizontal, low profile Teflon cylinder, this was a vertical cylinder to greatly reduce the probability of solution escaping at the vapor exit. Other improvements included a conical inner surface to allow for more consistent gathering of concentrated solution, a large vapor opening to restrict refrigerant flow as little as possible, and a rigid, external insulation block to provide a high level of heat loss control.

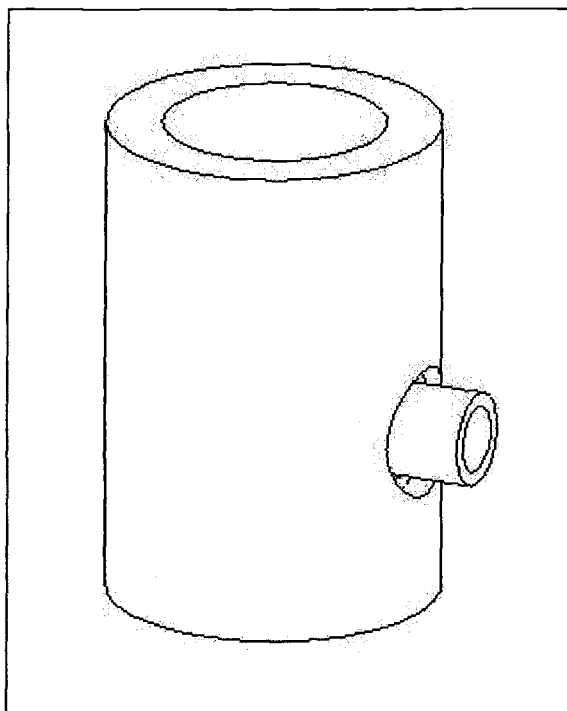


Figure D.3: Representation of separation chamber #3.

The separation chamber #3, while not ideal, proved to be adequate for desorption testing. Measurements were more consistent than the previous iterations, condensation within was greatly reduced and no Lithium Bromide escaped into the vapor stream. All data presented here were collected using this chamber design. For greater detail on this chamber, see Appendix 4.

Microchannel

The microchannel and heater combination are truly what make up the desorber. The LiBr-water solution boils as it flows through the channel, before entering the separation chamber.

Single Channel #1

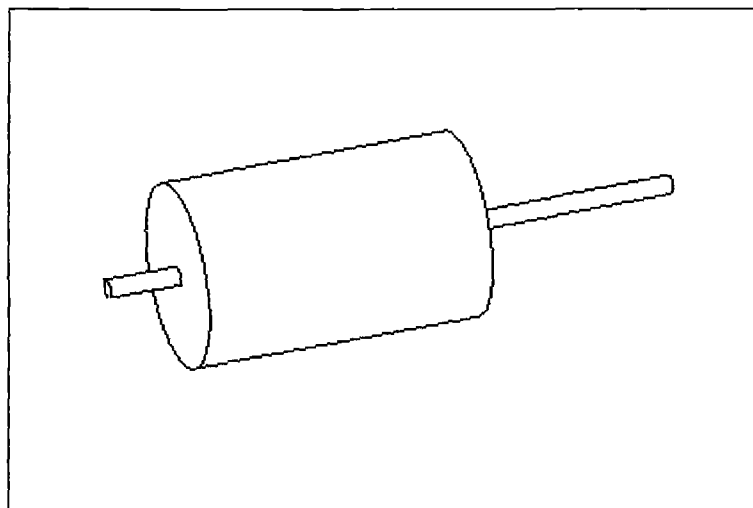


Figure D.4: Representation of single channel desorber #1.

The first microchannel, shown in Figure D.4, test section was prepared using a commercially available 316 stainless steel tube, 1/16 inch outer diameter, 0.127 mm channel diameter, and 5 cm long. While these dimensions were not ideal for a desorption system, this channel allowed for conventional fittings, and could be purchased in small volume at reasonable cost. The tube was placed inside an aluminum cylinder, which was then wrapped in a Kapton heater. The aluminum cylinder was not pressfit over the channel, as the channels often needed to be replaced due to corrosion and particulate obstruction. However, a layer of thermal grease was applied to the tube surface each time the heating cylinder was replaced. The exit of

the channel fit tightly within a Teflon plug that connected to the separation chamber, protecting the aluminum surface from corrosion.

This configuration allowed for initial tests to prove that the microchannel desorber was possible. During tests vapor was visible and boiling apparent. However the 5 cm length led to excessive pressures at the channel entrance. The high pressures were within the capacity of the syringe pumps, in the range of 150 kPa, but were excessive for a desorption system. Also, the Teflon barrier proved to be problematic. While the plug initially held a close seal, after assembling and re-assembling the device several times it began to leak at the channel exit. The leak was small, but large enough to disrupt measurements and corrode the metal.

Single Channel #2

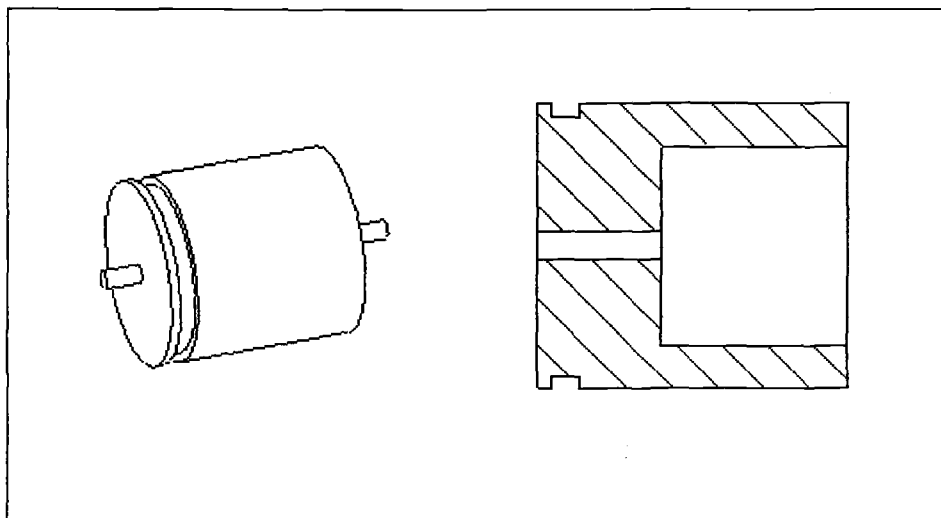


Figure D.5: Representation of single channel desorber #2.

Design #2, displayed in Figure D.5, was prepared as a way to use a shorter, 2.5 cm channel while still incorporating standard fittings and heaters. The ½ inch wide Kapton heater wrapped around the aluminum cylinder, while leaving enough room for an o-ring seal. The hollowed out inner portion was required to provide sufficient channel length for the conventional fittings used. The 2.5 cm channel brought the pressure range to a more reasonable value, generally under 70 kPa for most flow rates. As with the first channel design, the cylinder fit snugly and heat transfer was augmented with thermal grease. Also, the front face of the cylinder was coated in a thin layer of silicone to protect the metal. Though the seal was not perfect, the aluminum sections were easy and inexpensive to replace when the corrosion became significant.

Further observational tests were made possible with this microchannel design, but the heat transfer area was too small, and the channel could not be permanently fixed in the heating cylinder. Both of these problems introduced excessive variability and decreased the desorber efficiency.

Single Channel #3

Figure D.6 displays the final design for single channel testing, prepared to address the flaws of both previous systems. All of the single channel results displayed in this report were collected using this device. The same 2.5 cm channel, 0.5 inch Kapton heater and conventional fittings were used, allowing for low pressures, low

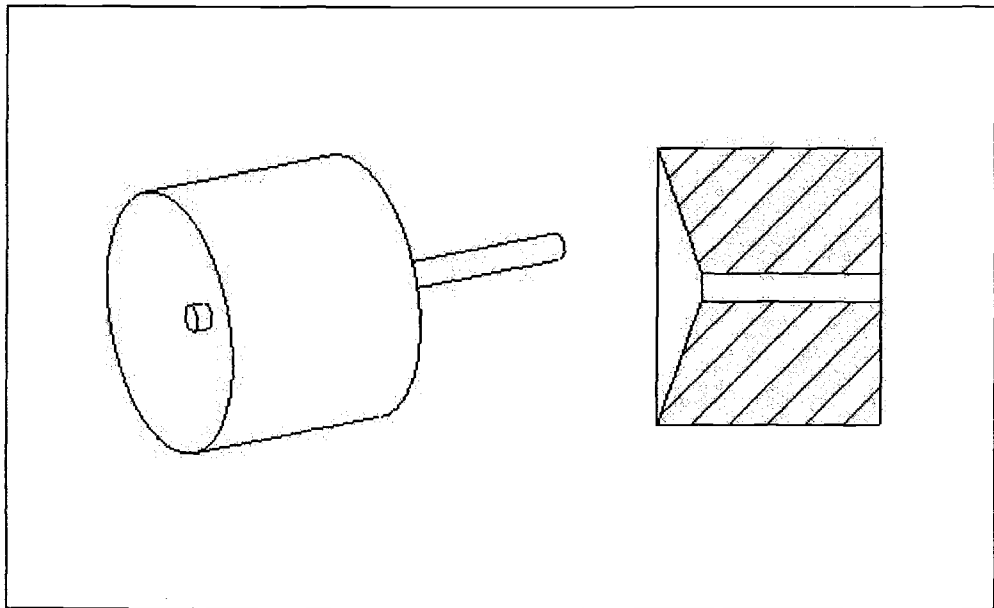


Figure D.6: Representation of single channel desorber #3.

costs and tight fluid connections. However, a coned front surface on the aluminum cylinder allowed for an increase in contact area between the cylinder and the channel, permitting for more reasonable heat transfer rates to the channel surface. Again the exposed aluminum was sealed with silicone. Also, by exposing the fittings outside of the heating cylinder the channel section could be removed from the test loop without removing the heating cylinder from the channel. Thus, heat transfer rates were more consistent and the set-up process was less complex.

Multi-channel #1

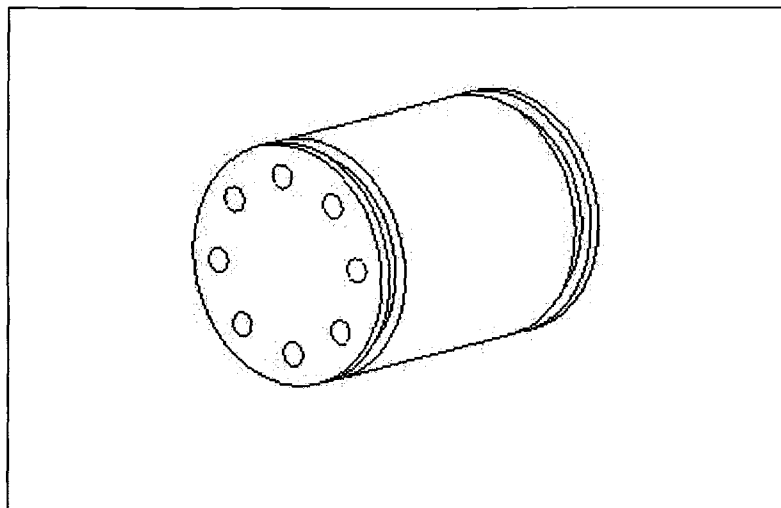


Figure D.7: Representation of multi-channel desorber #1.

Multi-channel #1, shown in Figure D.7, was the first attempt made to measure how the microchannel desorption works on a larger scale. This was an aluminum cylinder, with eight 0.127 mm microchannels pressed into radial holes. The channels were identical to the 2.5 cm channels used in single channel testing, and were purchased commercially. The eight channels were held anchored within a single Teflon plenum by an o-ring to allow for near uniform pressure distribution. The exit of the channels was sealed to the separation chamber by a similar o-ring. A ½ inch Kapton resistance heater was fixed to the cylinder using silicone stretch tape to provide a controllable heat source.

During testing, some flaws were immediately apparent. First, though the eight channels shared a reservoir, gravitational forces led to significantly greater flow in the lower channels. This flow imbalance led to hot spots, unnecessarily high pressures, and local crystallization of the Lithium Bromide within the upper channels. Second, the aluminum face was prone to severe corrosion. While a thin layer of silicone temporarily protected the metal from damage, it was insufficient long-term. And due to the complexity of the part and the cost of replacement tubing, continuously changing the entire desorber was not practical. Third, the heated face, both within the reservoir and within the separation chamber, added an additional source of uncertainty, as the precise inlet temperature could not be determined, and additional boiling could occur as the solution dripped down the out face. Finally, the o-ring seal could not hold the necessary pressures within the reservoir. Leaks were significant and persistent.

Multi-channel #2

Multi-channel #2, shown in Figure D.8, addressed many of the flaws associated with multi-channel #1. Also, this design provided a more direct comparison to large array, parallel channel desorbers which would likely follow. The channels were manufactured by Tom Tseng of Oregon State University IE Department by laser-cutting thin titanium, then diffusion bonding the layers. Each channel section had

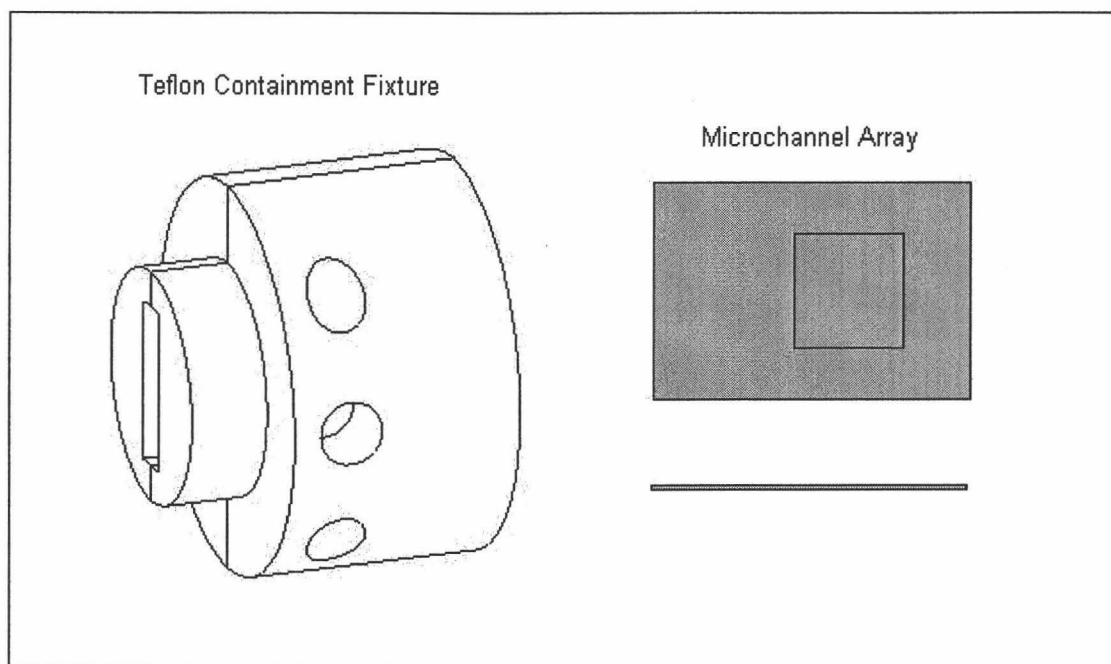


Figure D.8: Representation of multi-channel desorber #2.

five, square microchannels, each with a hydraulic diameter of about 0.130 mm. These channels were accessed through an open reservoir on the top face, allowing all five channels to receive nearly the same pressure. The manufacturing technique dictated a channel length of 8.5 mm. Longer channels were difficult to bond properly. The two titanium arrays were arranged on opposite sides of a Kapton heater, with two copper sheets to improve heat uniformity. Finally, a Teflon containment fixture, with integrated reservoirs, held the arrays together, and provided for the needed fluid and instrument connections.

While multi-channel #2 was a step forward, and allowed for the recorded data in this report, it was not without problems. The combination of Teflon and titanium countered the corrosion difficulties from the first multi-channel system. However,

despite Teflon's high melting temperature, it begins to soften and deform at about 120 °C. The combination of heat and compression eventually warped the o-ring grooves, making leaks more and more common. But the greater difficulty in this design was the pair of arrays. Slight differences in flow paths and configurations caused variation in the two flow rates. At low heat fluxes the variations were minor, but when boiling began sooner in the array with the lower flow rate, nearly all of the flow was redirected to the cooler array by the pressure difference. Thus one array was operating under subcooled conditions, while the other was boiling dry, leading to Lithium Bromide crystallization and heater hotspots. This instability forced testing done with these arrays to occur at a lower than optimal heat flux, removing the chance to properly study a direct scaling between the single and multi-channel systems.

Despite the deficiencies in multi-channel #2, this design did yield some important information. The instability observed in this design will plague most paired array systems unless it is properly addressed. The issue could be partially resolved by using a pump which provides a flow source rather than a pressure source. Further improvement would be possible by using a single array rather than a pair of arrays. The single array would require more volume for the same number of channels, and would require a heater capable of withstanding high temperatures, but it would allow for sufficient heat inputs to provide desorption. Also, despite Teflon's high corrosion and temperature resistance, and machinability it is not appropriate for components under stress. Further, its high rate of thermal expansion can affect otherwise secure fittings. Therefore, if a device similar to multi-channel #2 were to work properly, the

Teflon clamp would be replaced with another material, perhaps titanium, using larger o-rings to compensate for the increased rigidity.

Preheater

The preheater is intended to raise the temperature of the bulk solution to nearly boiling to allow for smaller heat fluxes and shorter length in the microchannel. While a working vapor-absorption chiller would not make use of a preheater, the component compensates for two drawbacks of the current lab set-up: atmospheric pressure and electric heating. At atmospheric pressure, Lithium Bromide-water solution boils at about 140 °C. Under the low pressure conditions in a working chiller, the same concentration solution boils at about 95 °C, making less heat necessary to reach boiling. Also, microchannels heat liquid at such a high heat transfer coefficient that most electric heaters cannot produce the required Watt density. Thus a preheater allows the heat input to be functionally divided.

Preheater #1

Preheater #1, shown in Figure D.9, was a hollow 304 stainless steel cylinder with tube fittings screwed into both ends. This heater allowed for conventional fittings, easy insulation with fiberglass batting, and consistent heating rates. However, the 304 stainless steel rapidly corroded with the heated LiBr-water solution.

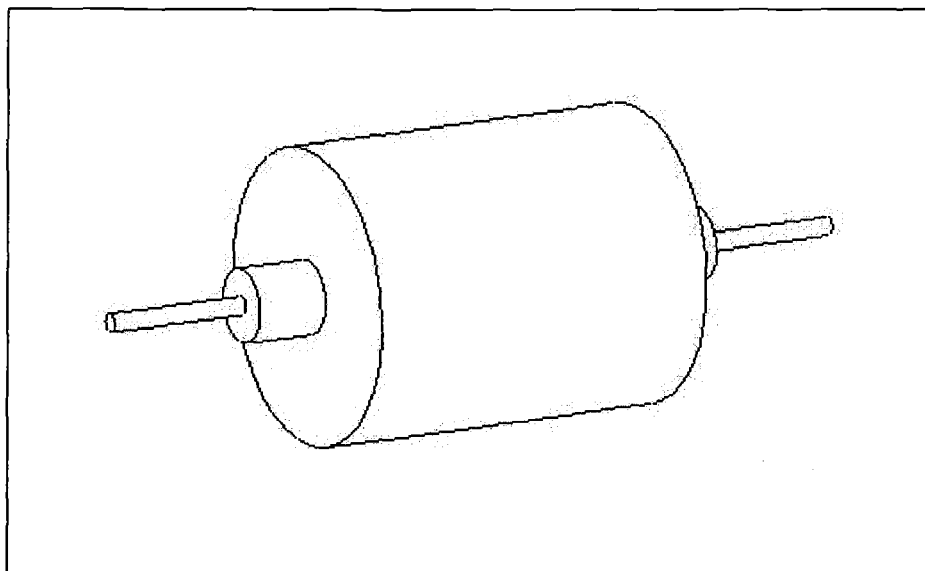


Figure D.9: Representation of preheater #1.

Preheater #2

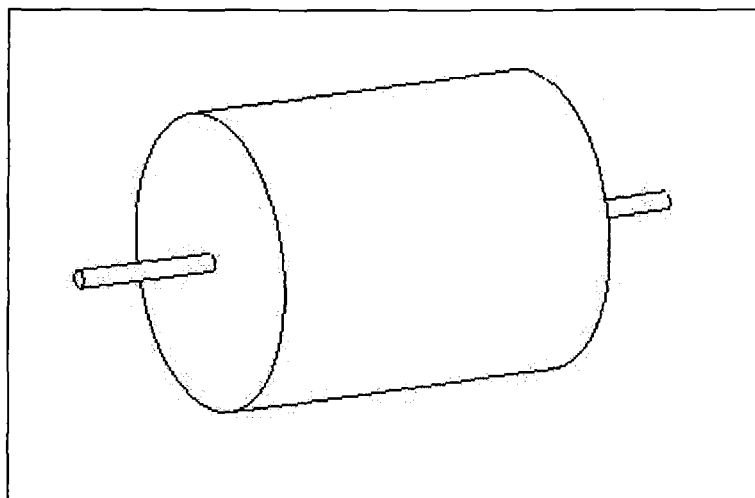


Figure D.10: Representation of preheater #2.

Preheater #2 addressed the corrosion difficulties from preheater #1 by pressing a 316 stainless tube into an aluminum cylinder. As visible in Figure D.10, this

preheater was a simple design intended to minimize damage to parts and contamination of the flow. Also, the switch to aluminum decreased the thermal resistance between the heater and the solution. But tests with this preheater produced flawed data. It was discovered that despite exit temperatures below saturation, boiling was occurring inside the preheater. As microscale boiling was the focus of this study, the preheater boiling invalidated all data taken with this configuration. Further, the large-scale boiling led to excessive and irregular pressure spikes that overwhelmed the small-scale phenomena studied.

Preheater #3

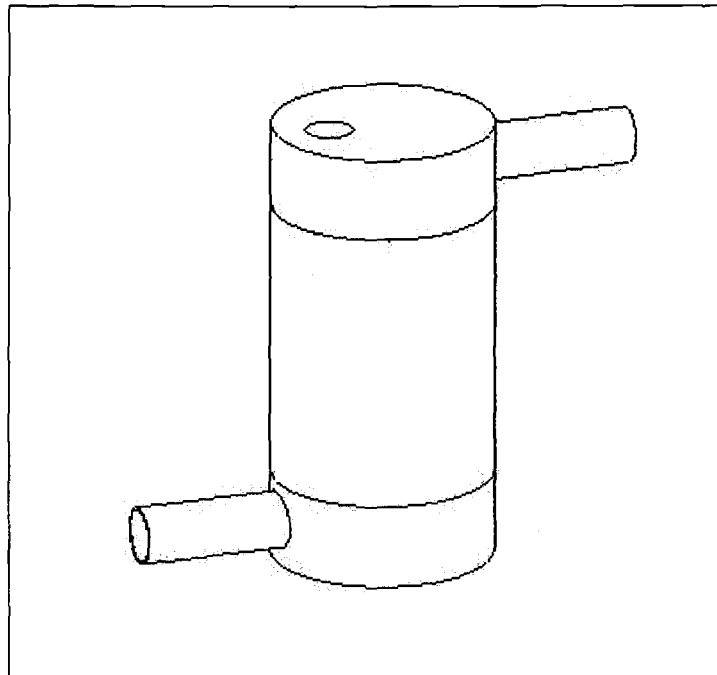


Figure D.11: Representation of preheater #3.

Figure D.11 displays the third preheater design. This device consisted of a large, vertical titanium tube, with fitted titanium endcaps and Inconel tubing for the inlet and exit, sealed with high temperature epoxy. The same 1 inch band heater was placed around the titanium tube for heating the bulk fluid. A thermocouple was inserted into the top of the cavity to document the device temperature and ensure that no boiling occurred. Also, the vertical orientation ensured that any trapped gases or vapor remained in the cavity rather than continuing into the microchannel system. This device was largely successful, and was used for all of the single channel data presented in this report.

Preheater #4

Though preheater #3 was initially able to supply the required, heated flow, the epoxy used in sealing cracked over time. Though the temperatures within the cavity were well within the range for the epoxy, the difference in rate of thermal expansion between the titanium and sealant led ultimately to cracks and leaks. Preheater #4, shown in Figure D.12, was designed and manufactured to counter that problem. The main cavity was again made from 1 inch titanium tubing, however the ends were tightly press-fit rather than epoxied together. Also, the wide base allowed for a stable, free

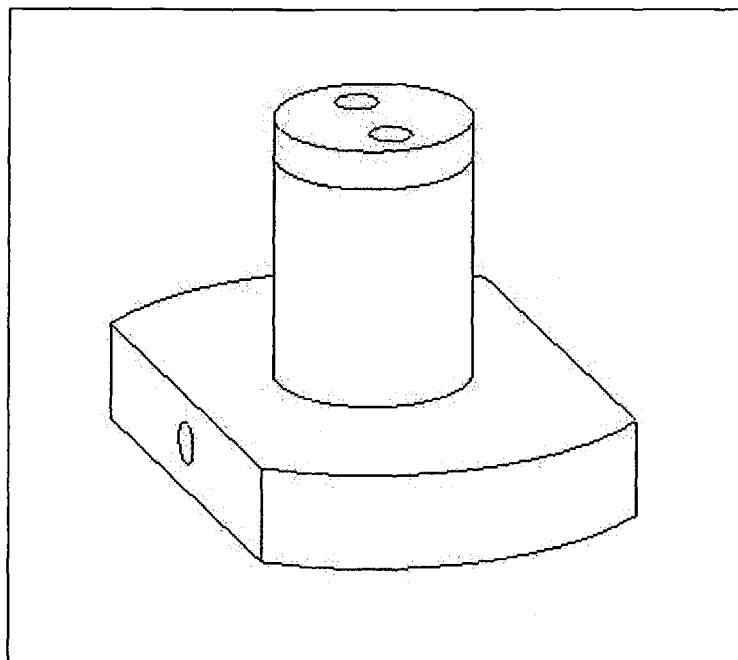


Figure D.12: Representation of preheater #4.

standing device, requiring no additional support. But despite the close fit in the machine parts, epoxy still had to be applied at the joints to prevent leaking. Preheater #4 was used for all multi-channel tests.

Insulation

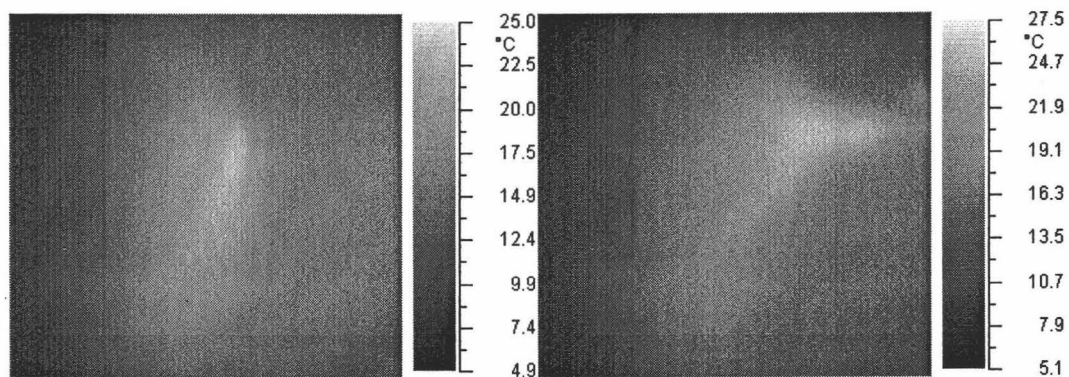
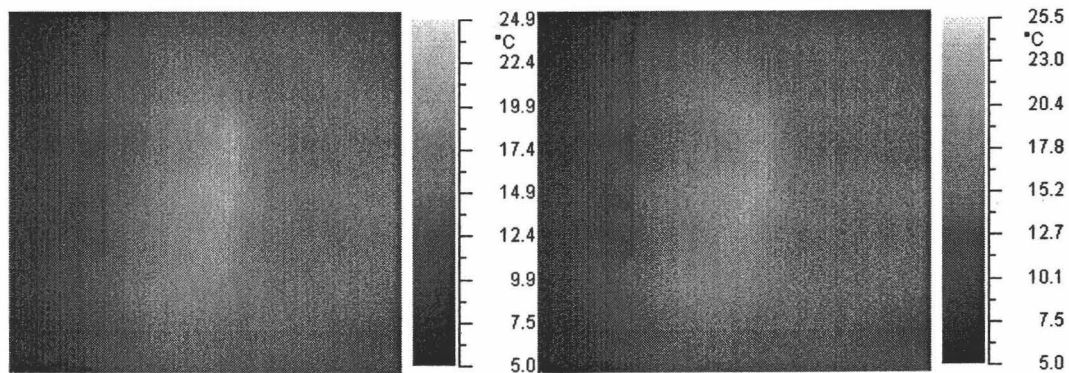
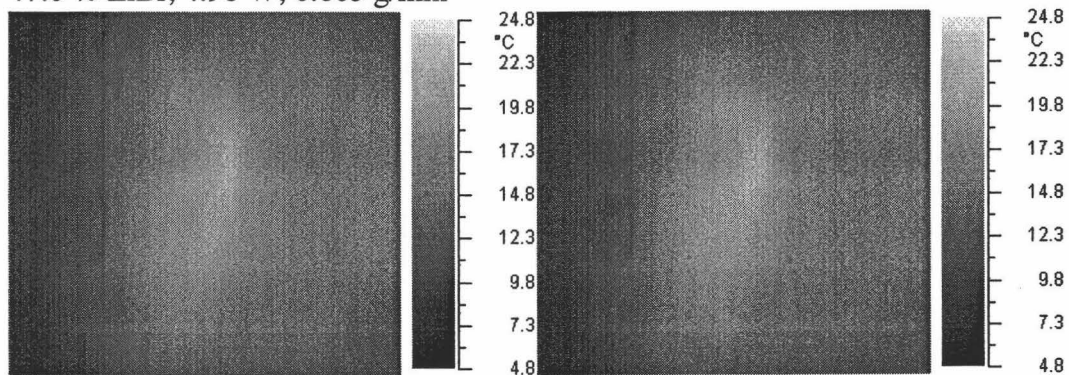
LiBr-water solution boils in an awkward temperature range. It is too hot for standard foams and polymers, but does not require the extreme materials used in high temperature situations. Initial tests were done with bare Teflon, as fluoropolymers insulate reasonably well on their own. When that level of insulation proved to be insufficient, components were wrapped in fiberglass batting. While the fiberglass

provided adequate insulation it was inconvenient to wrap and unwrap components, and the insulative value was inconsistent due to alterations in the wrapping. To counter these difficulties, profiles of all of the parts were machined into a Calcium Silicate block, which provided both a rigid structure for the flow loop and consistent insulation. However, the Calcium Silicate is intended for high temperature conditions and had inadequate low temperature performance. Also, the machined surfaces continuously produced a fine dust, which began to contaminate the flow system. Finally, a similar profile was machined into a large block of cork. The cork provided better insulation than the Calcium Silicate, and removed the dust from the environment while still supplying a consistent, supportive structure.

Appendix E: Thermal Images

Note: All temperature scales are relative.

47.0 % LiBr, 4.98 W, 0.603 g/min



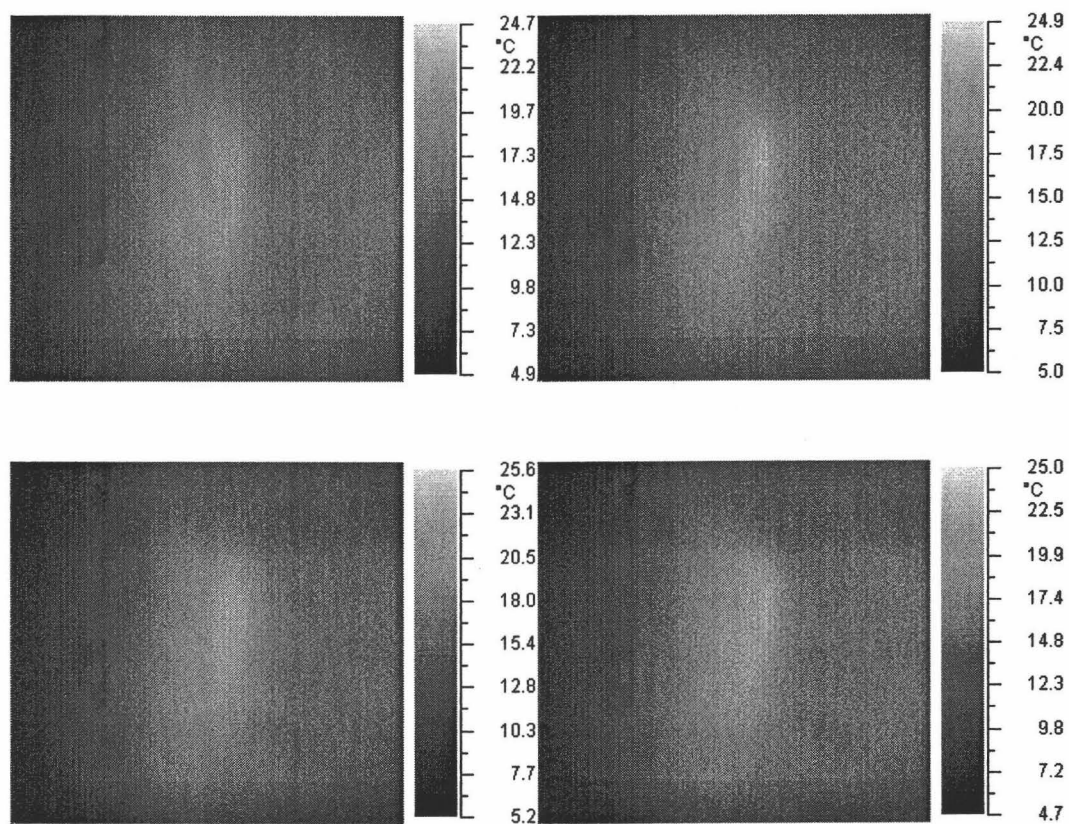


Figure E.1: Thermal visualization of 0.127 mm microchannel exit, 47.0 % LiBr, 4.98 W, 0.603 g/min, 0.0644 ms shutter speed.

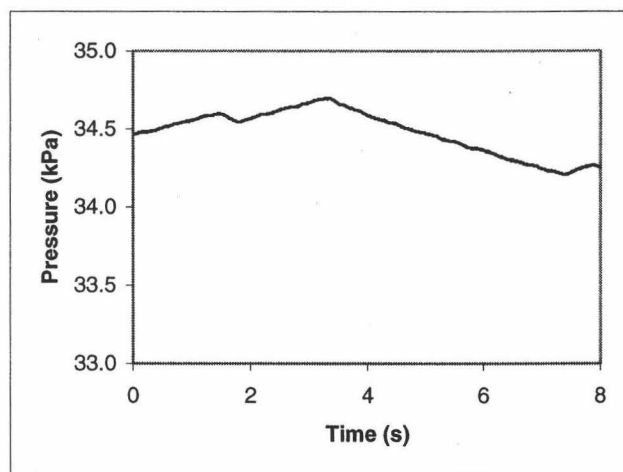
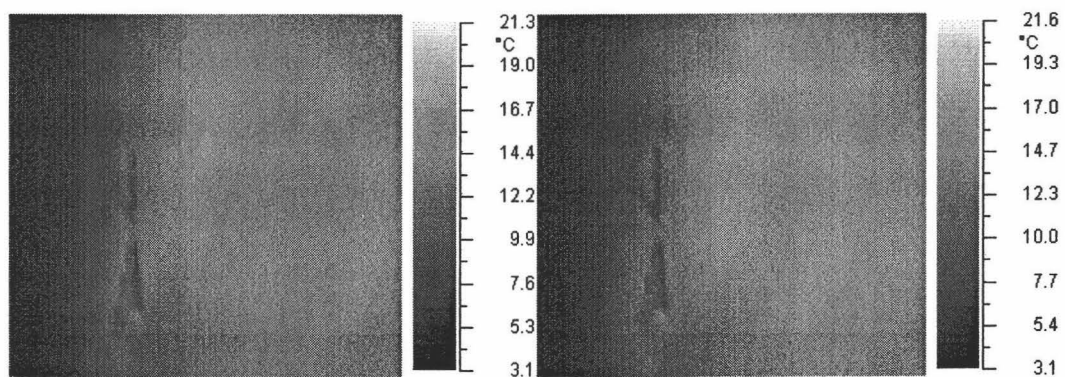
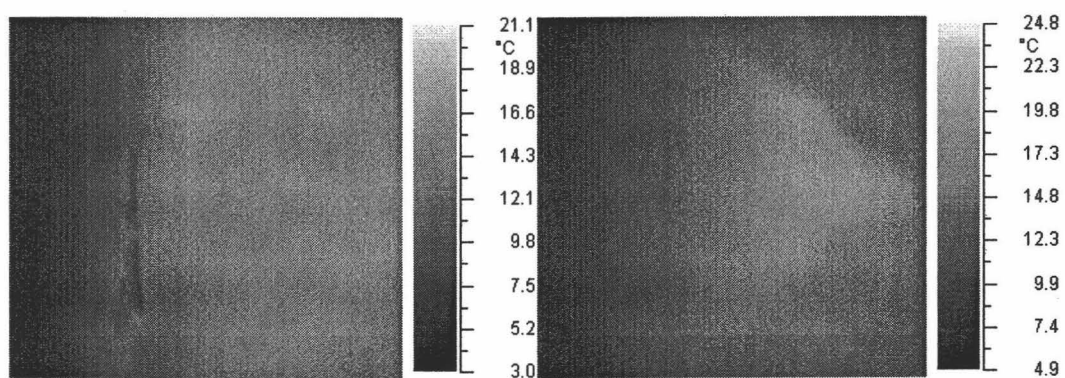
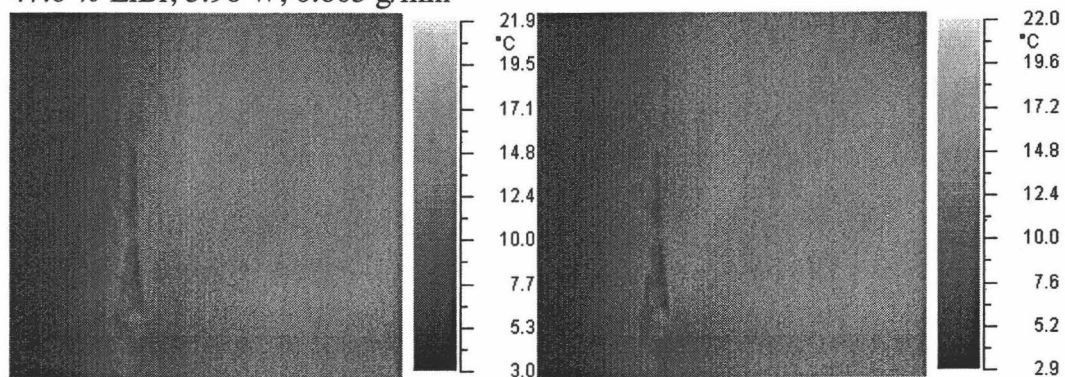


Figure E.2: Pressure response over 8 seconds at 100 Hz, single 0.127 mm channel, 4.92 W, 0.60 g/min, 47 % LiBr.

47.0 % LiBr, 5.96 W, 0.603 g/min



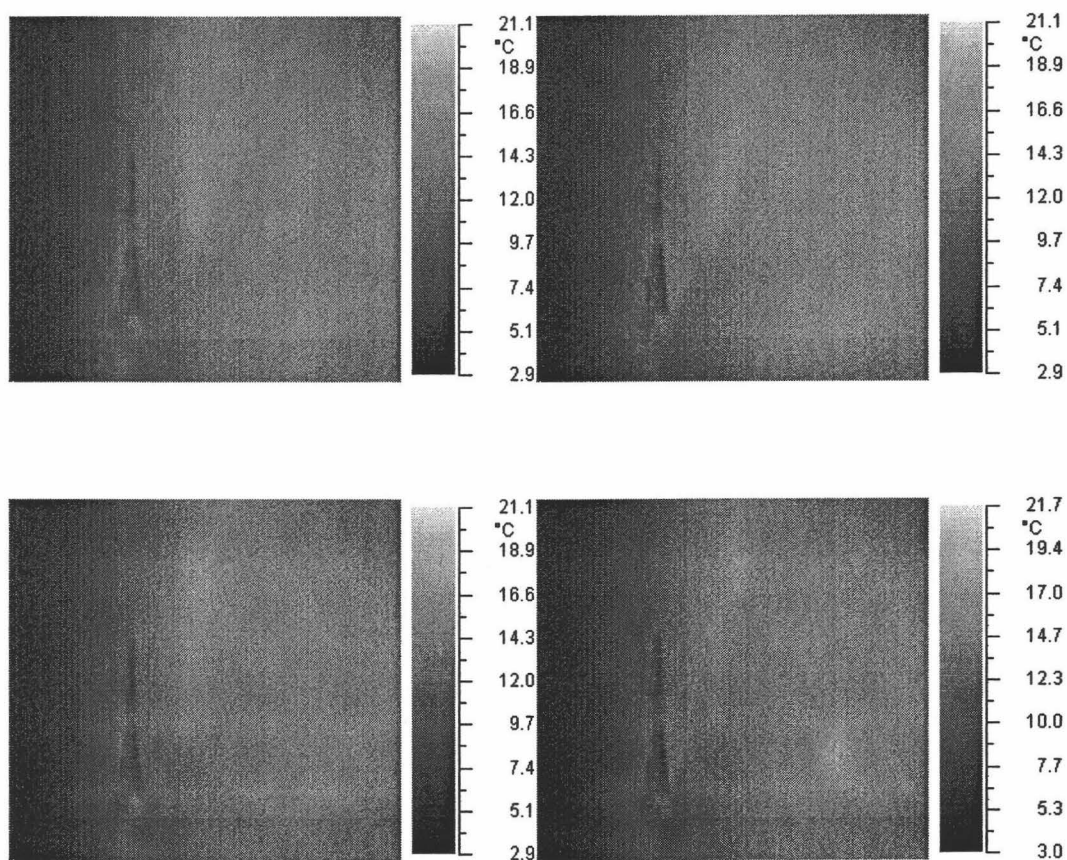


Figure E.3: Thermal visualization of 0.127 mm microchannel exit, 47.0 % LiBr, 5.96 W, 0.603 g/min, 0.0644 ms shutter speed.

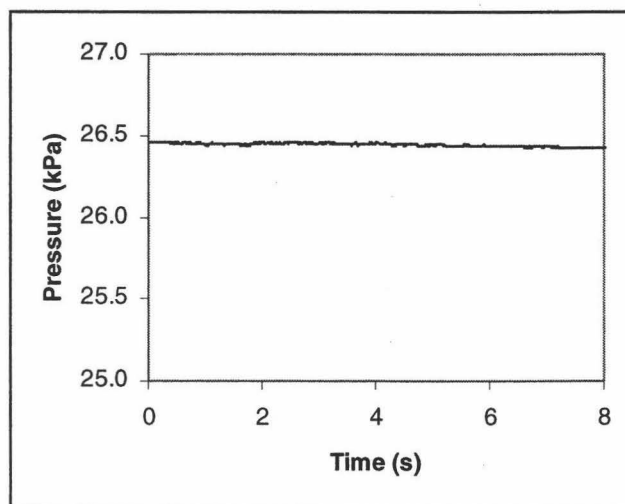
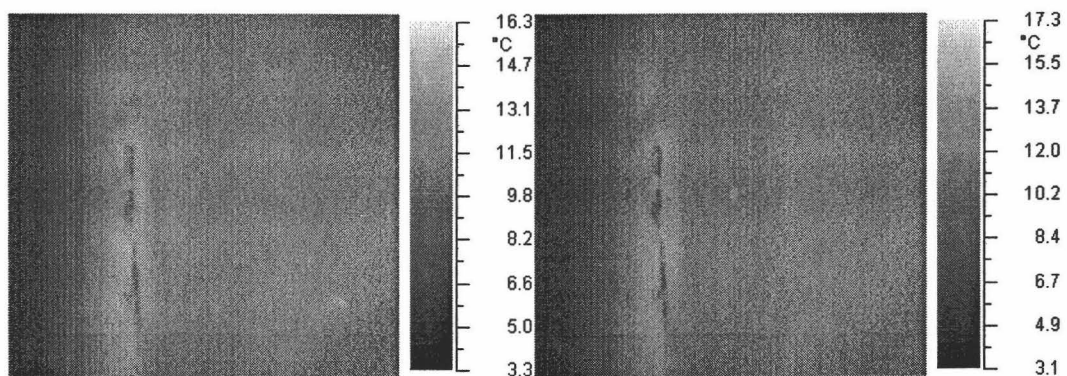
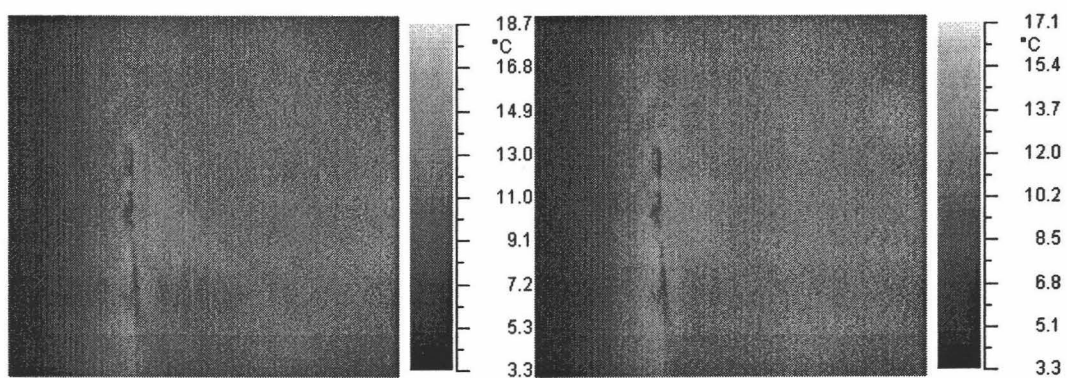
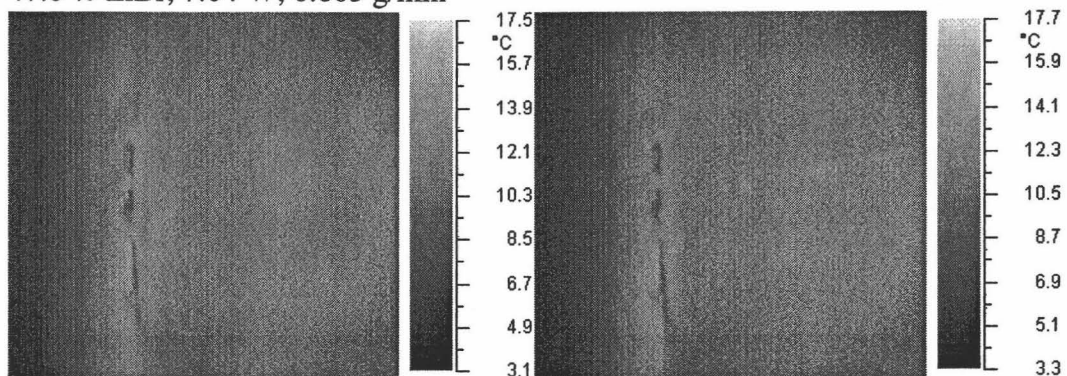


Figure E.4: Pressure response over 8 seconds at 100 Hz, single 0.127 mm channel, 5.96 W, 0.603 g/min, 47 % LiBr.

47.0 % LiBr, 7.04 W, 0.603 g/min



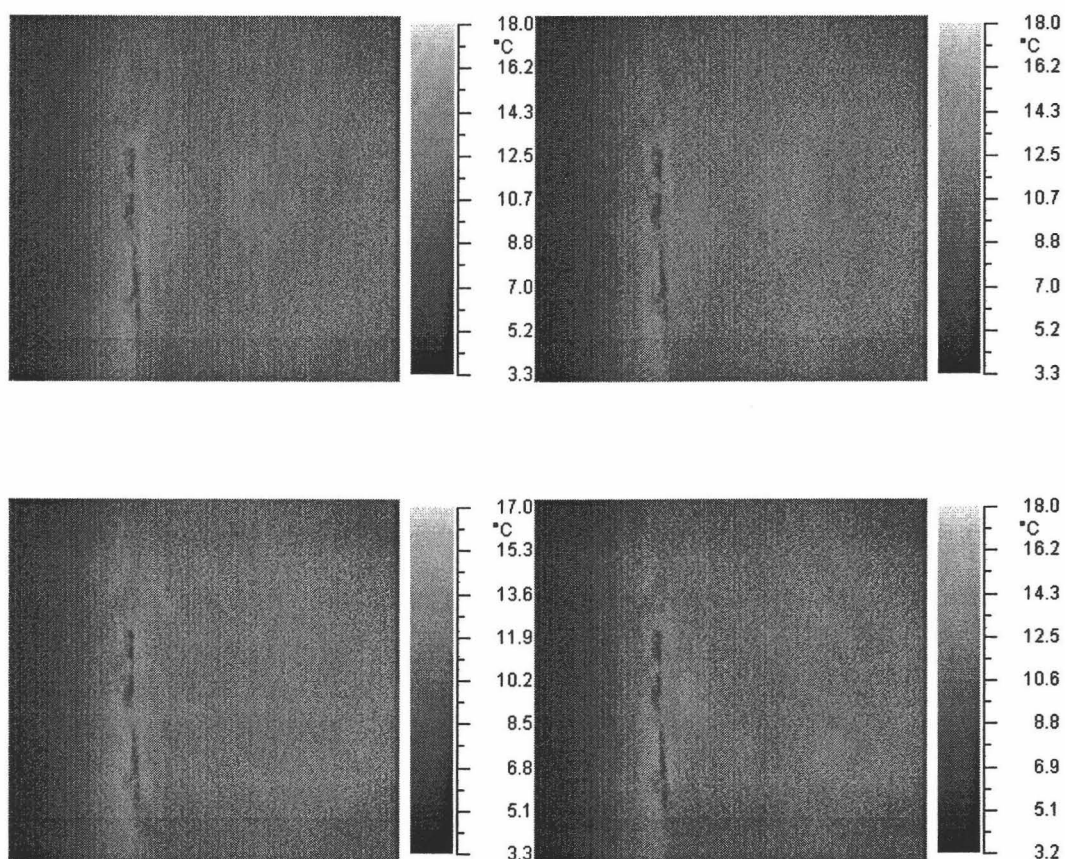


Figure E.5: Thermal visualization of 0.127 mm microchannel exit, 47.0 % LiBr, 7.04 W, 0.603 g/min, 0.0644 ms shutter speed.

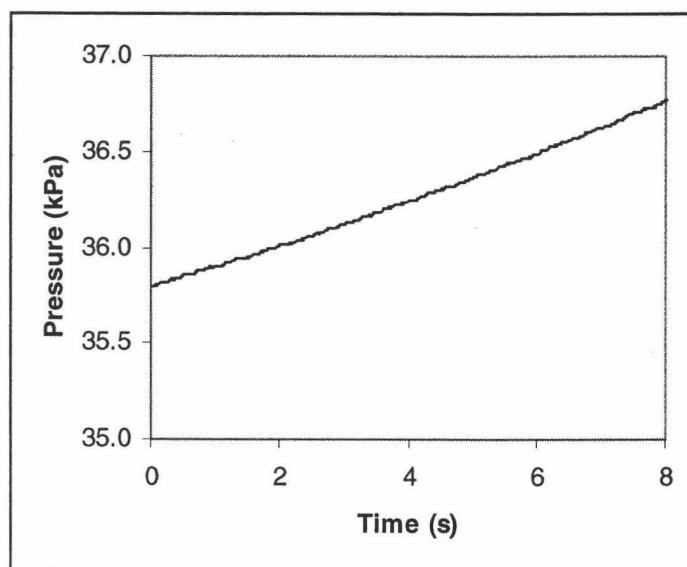
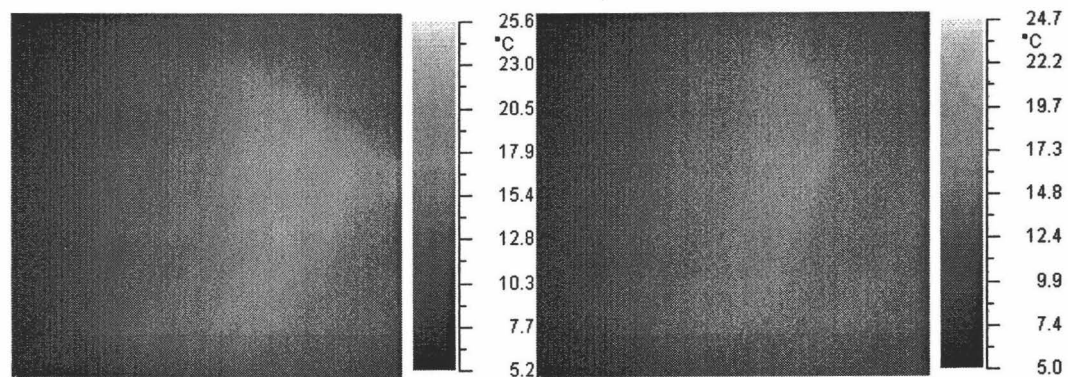
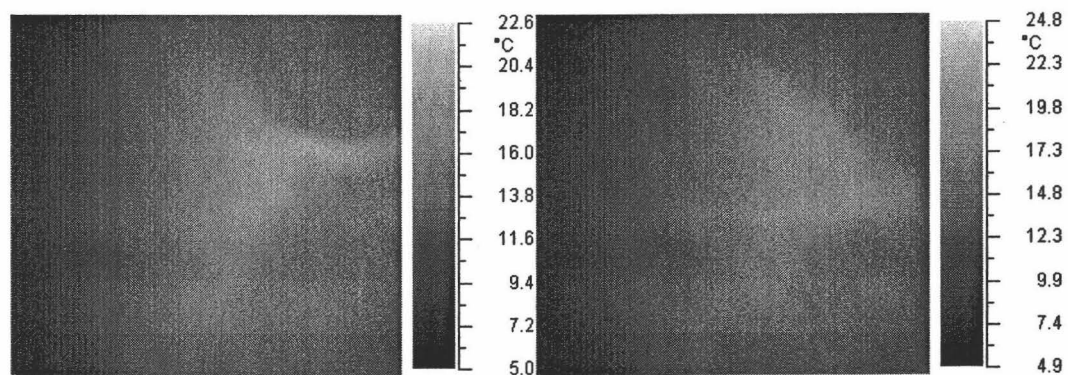
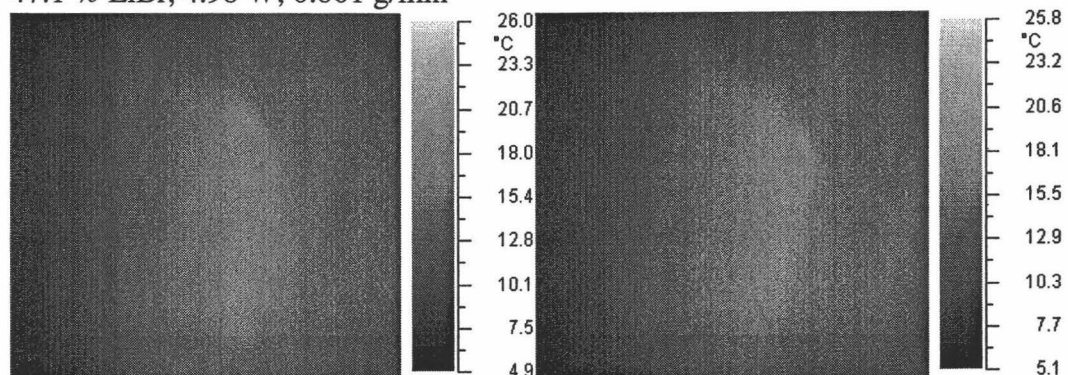


Figure E.6: Pressure response over 8 seconds at 100 Hz, single 0.127 mm channel, 7.04 W, 0.603 g/min, 47 % LiBr.

47.1 % LiBr, 4.98 W, 0.801 g/min



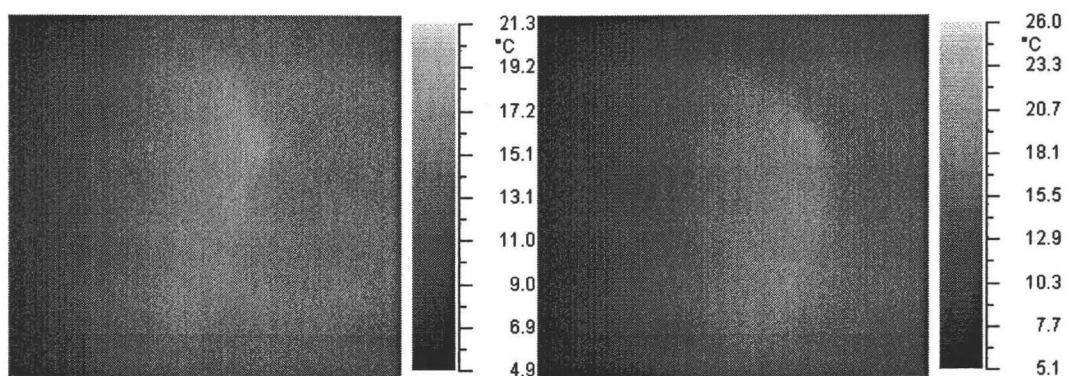
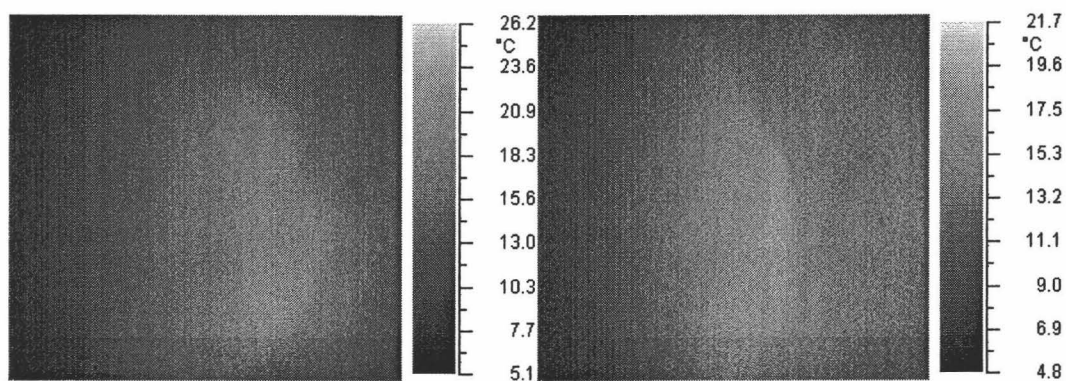


Figure E.7: Thermal visualization of 0.127 mm microchannel exit, 47.1 % LiBr, 4.98 W, 0.801 g/min, 0.0644 ms shutter speed.

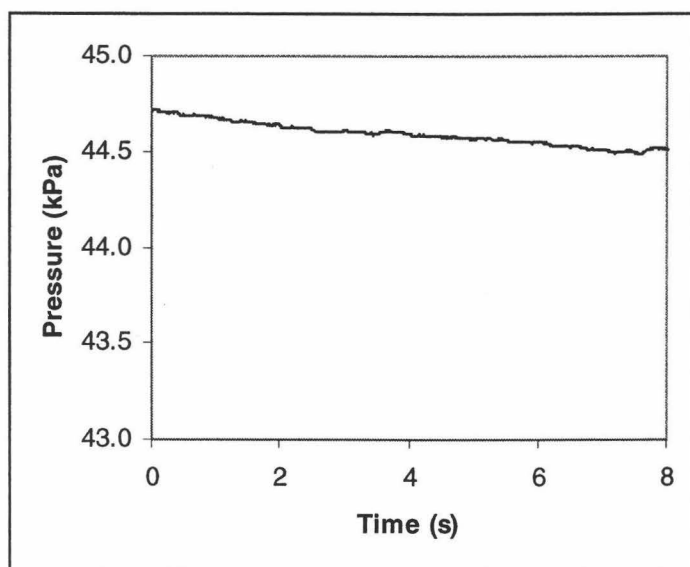
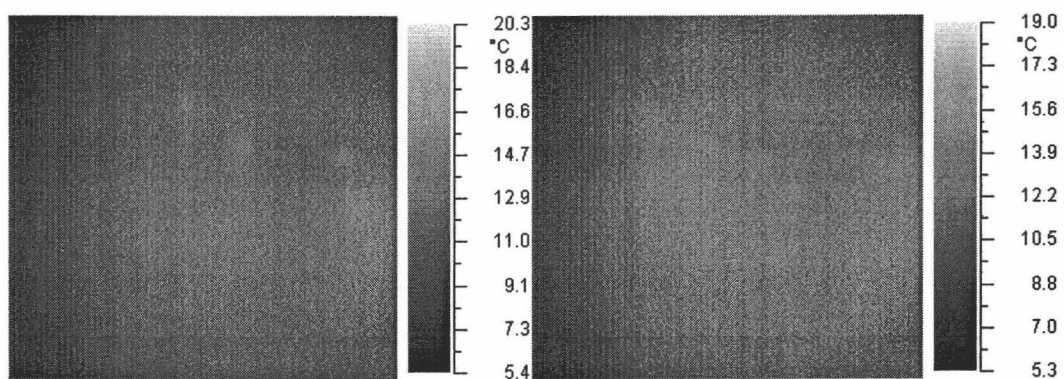
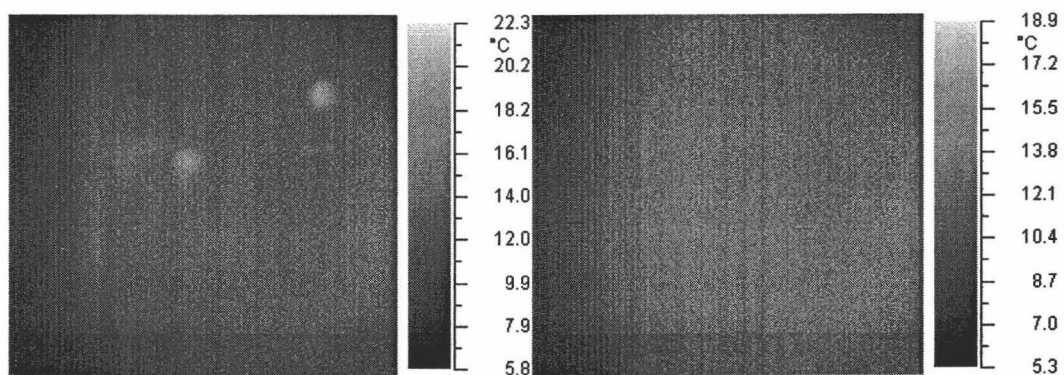
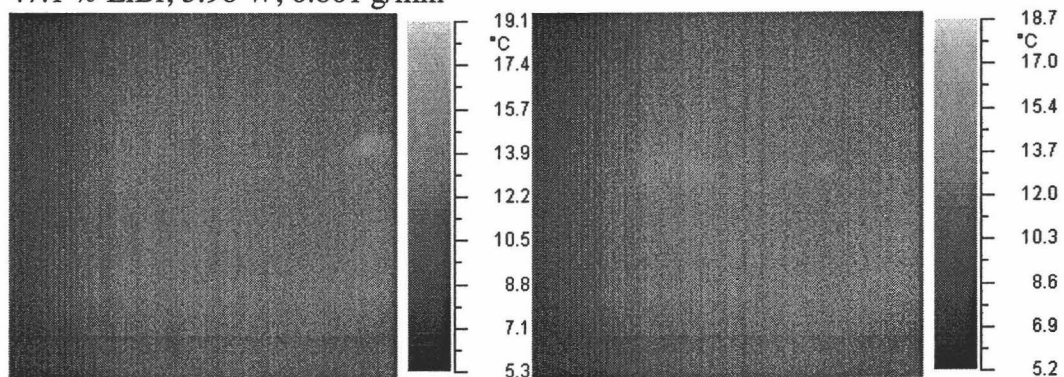


Figure E.8: Pressure response over 8 seconds at 100 Hz, single 0.127 mm channel, 4.98 W, 0.801 g/min, 47.1 % LiBr.

47.1 % LiBr, 5.96 W, 0.801 g/min



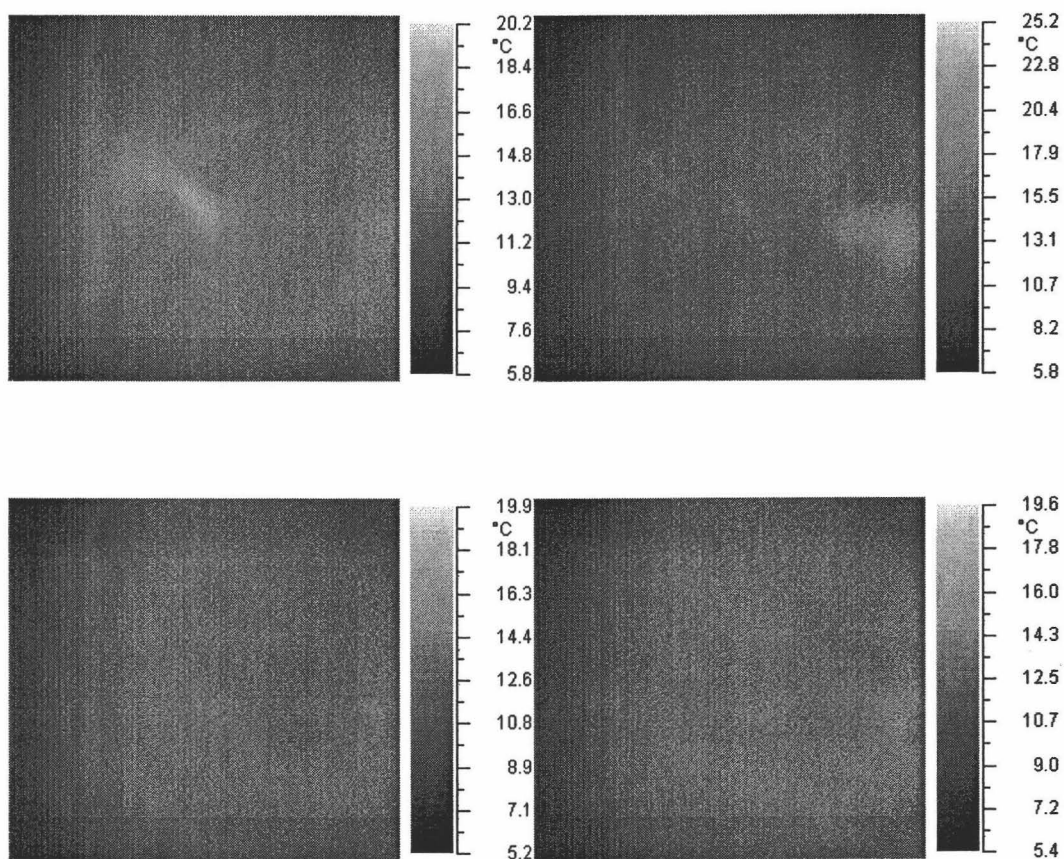


Figure E.9: Thermal visualization of 0.127 mm microchannel exit, 47.1 % LiBr, 5.96 W, 0.801 g/min, 0.0644 ms shutter speed.

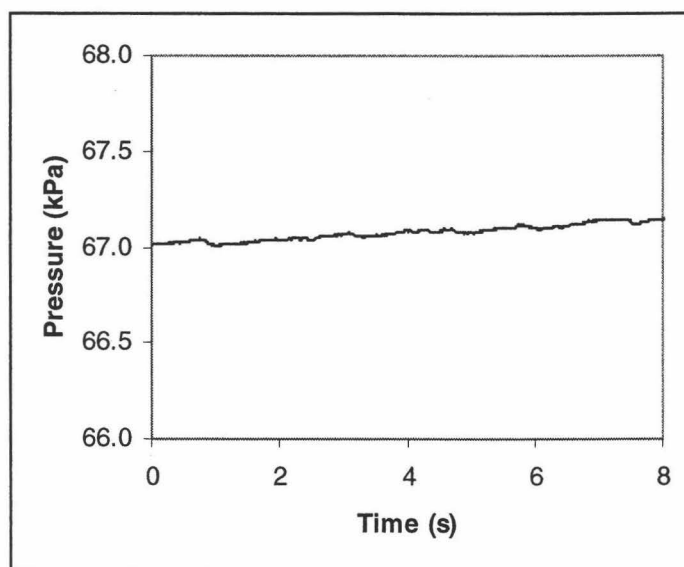
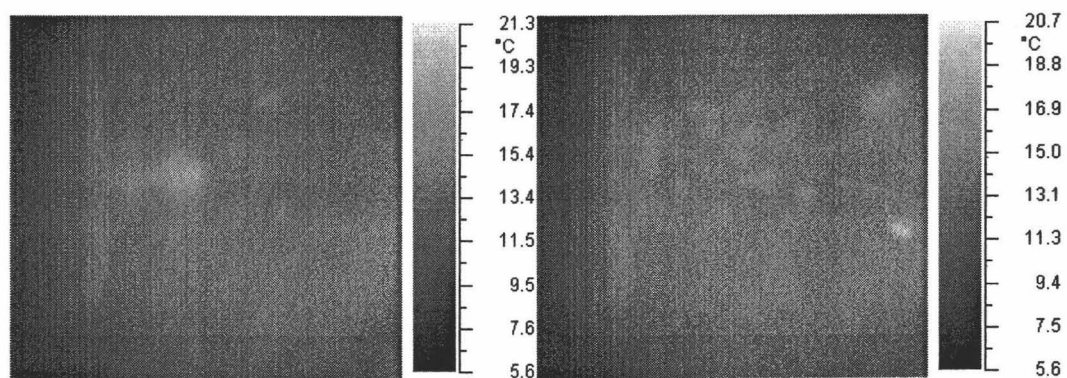
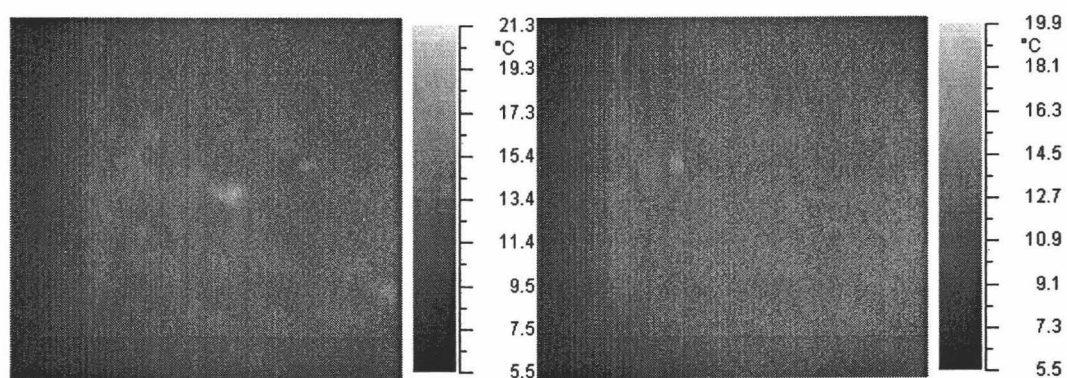
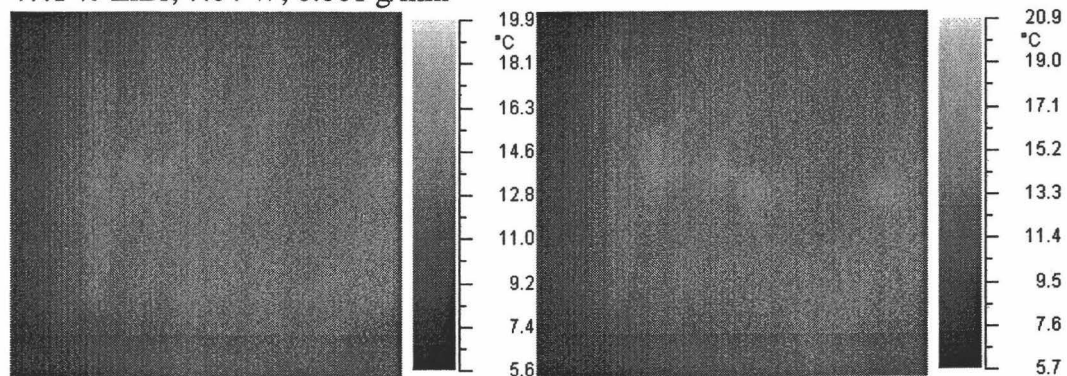


Figure E.10: Pressure response over 8 seconds at 100 Hz, single 0.127 mm channel, 5.96 W, 0.801 g/min, 47.1 % LiBr.

47.1 % LiBr, 7.04 W, 0.801 g/min



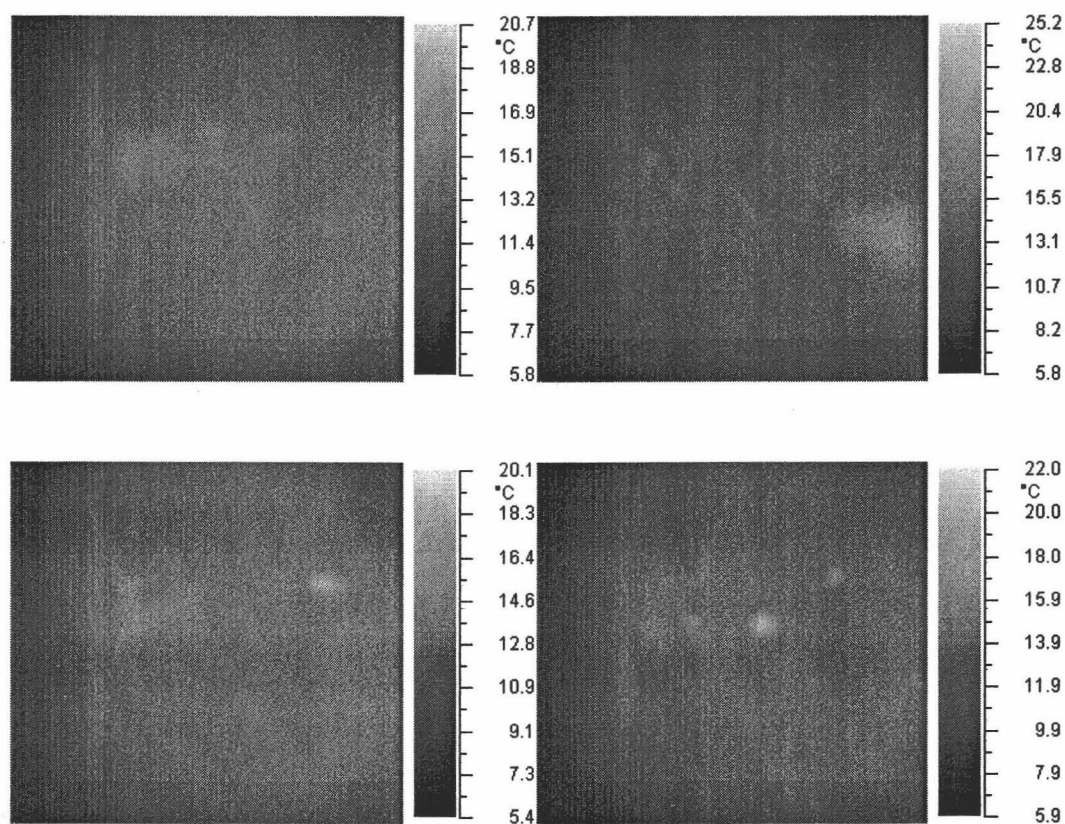


Figure E.11: Thermal visualization of 0.127 mm microchannel exit, 47.1 % LiBr, 7.04 W, 0.801 g/min, 0.0644 ms shutter speed.

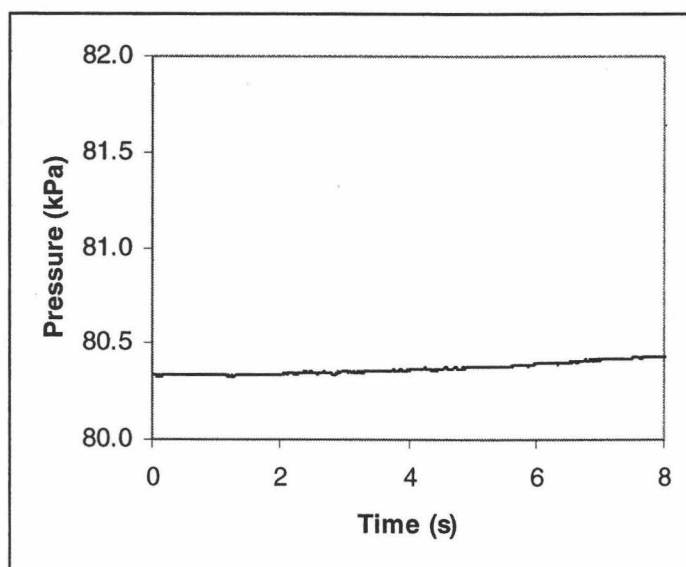
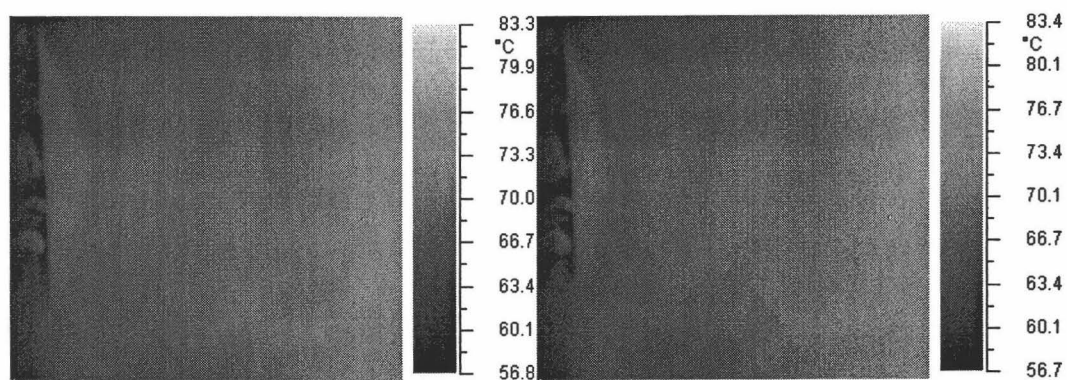
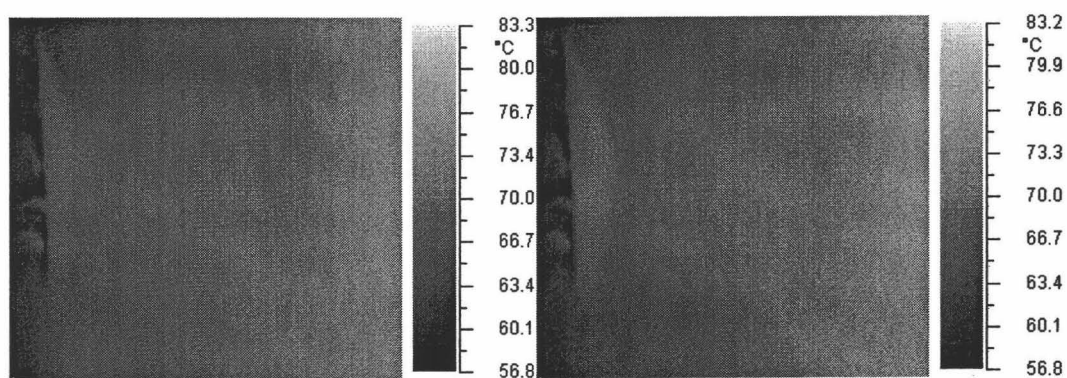
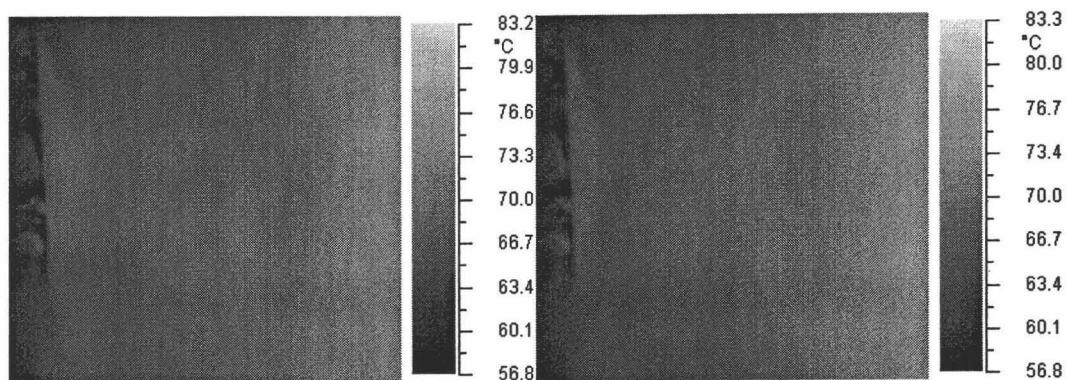


Figure E.12: Pressure response over 8 seconds at 100 Hz, single 0.127 mm channel, 7.04 W, 0.801 g/min, 47.1 % LiBr.

57.0 % LiBr, 4.98 W, 0.607 g/min



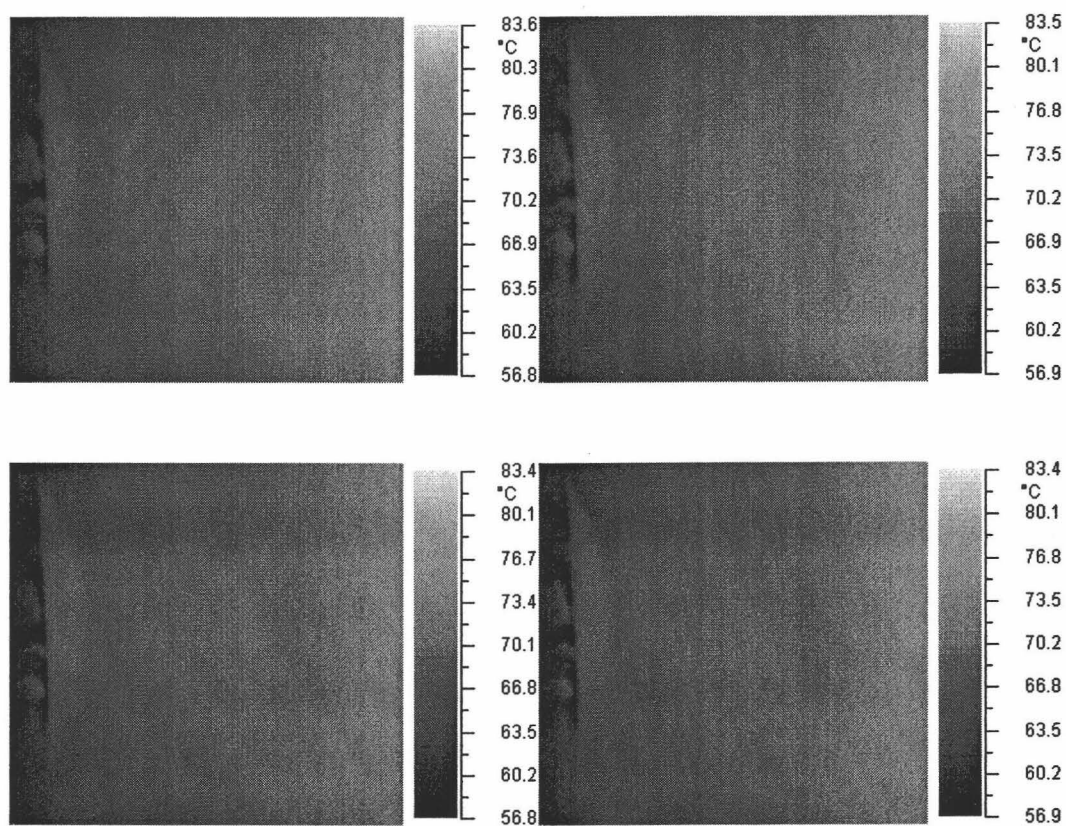


Figure E.13: Thermal visualization of 0.127 mm microchannel exit, 57.0 % LiBr, 4.98 W, 0.607 g/min, 1.256 ms shutter speed.

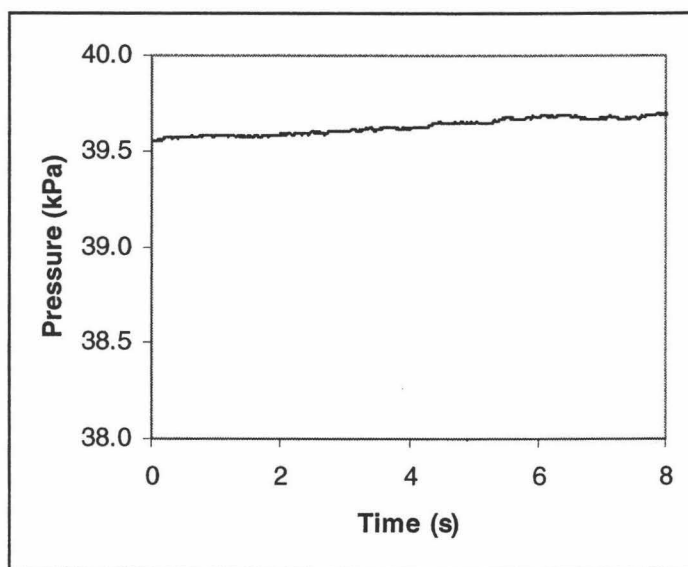
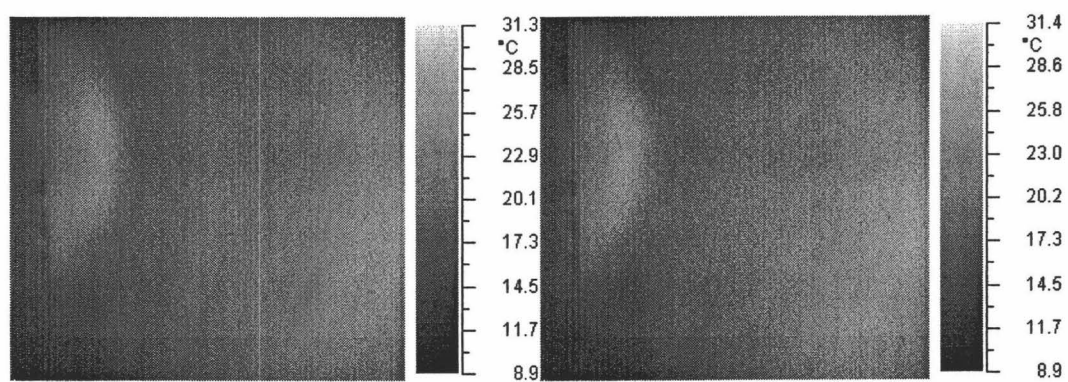
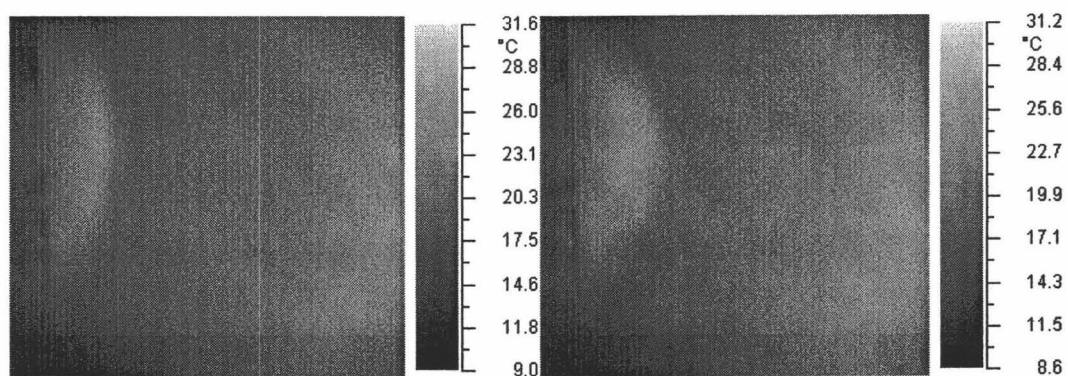
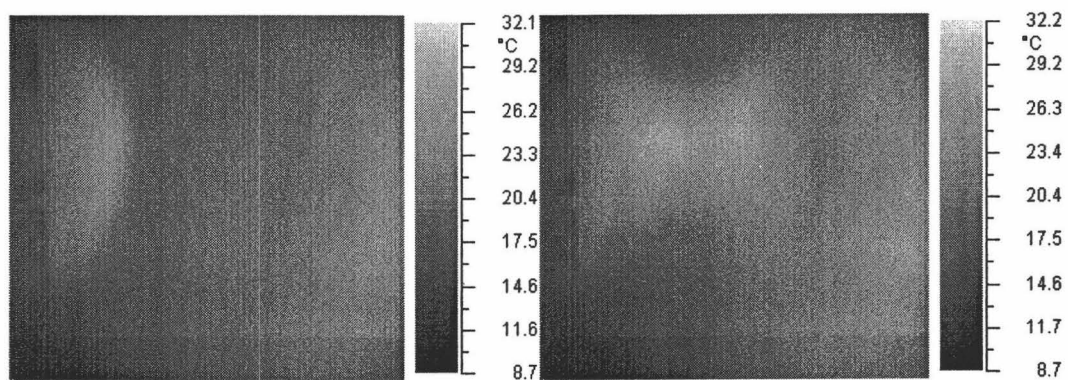


Figure E.14: Pressure response over 8 seconds at 100 Hz, single 0.127 mm channel, 4.98 W, 0.607 g/min, 57.0 % LiBr.

57.0 % LiBr, 5.96 W, 0.607 g/min



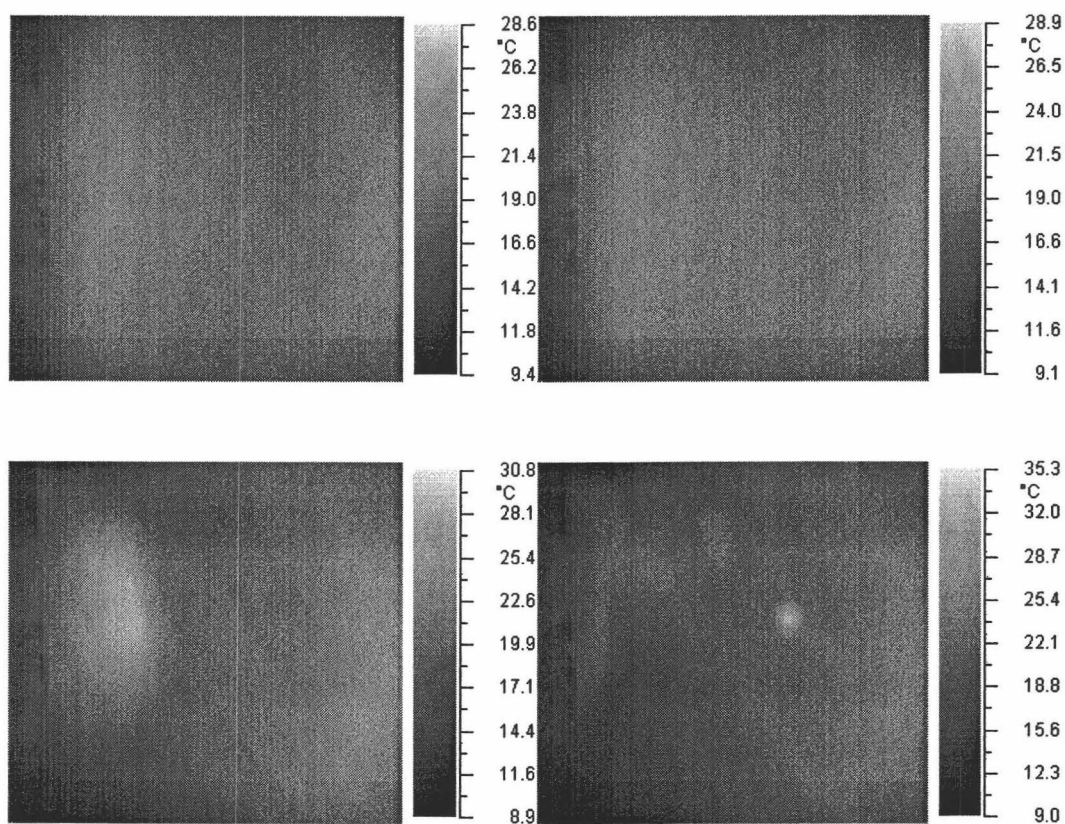


Figure E.15: Thermal visualization of 0.127 mm microchannel exit, 57.0 % LiBr, 5.96 W, 0.607 g/min, 0.0644 ms shutter speed.

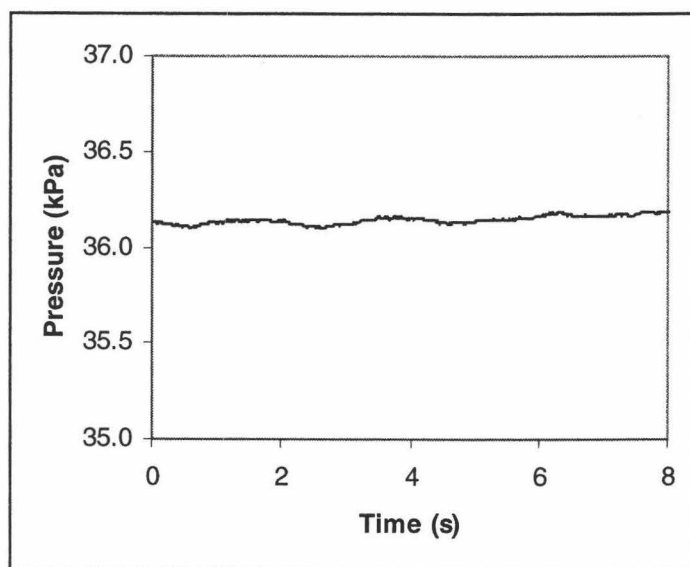
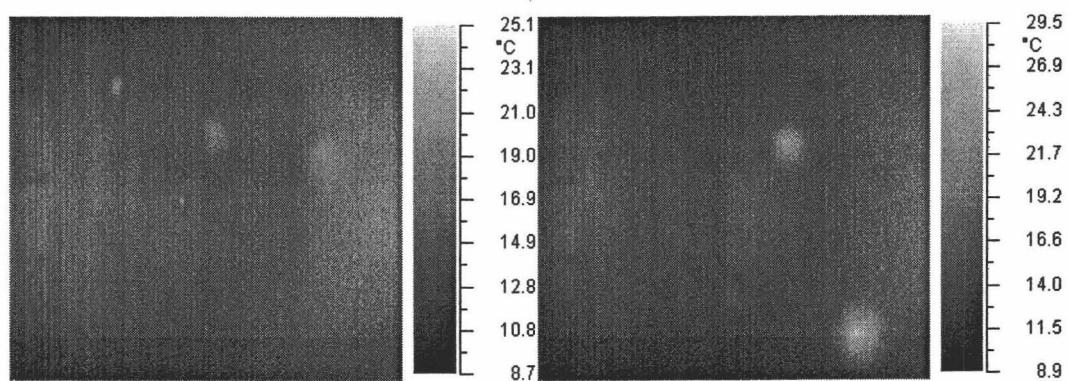
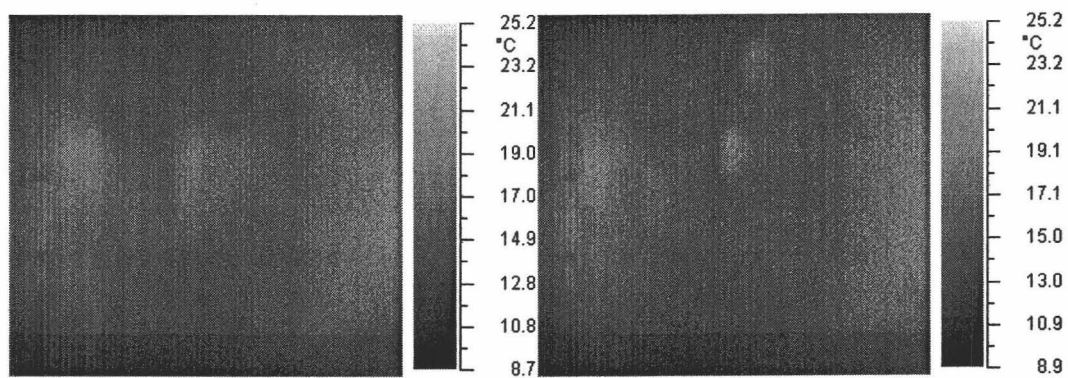
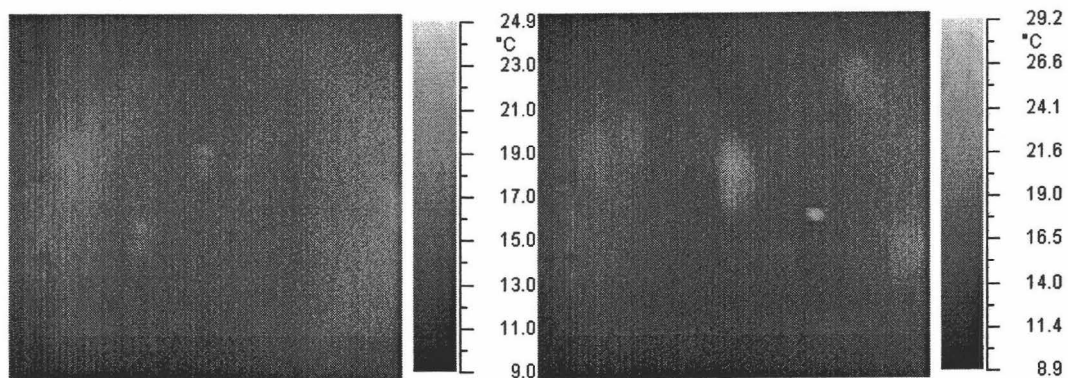


Figure E.16: Pressure response over 8 seconds at 100 Hz, single 0.127 mm channel, 5.96 W, 0.607 g/min, 57.0 % LiBr.

57.0 % LiBr, 7.04 W, 0.607 g/min



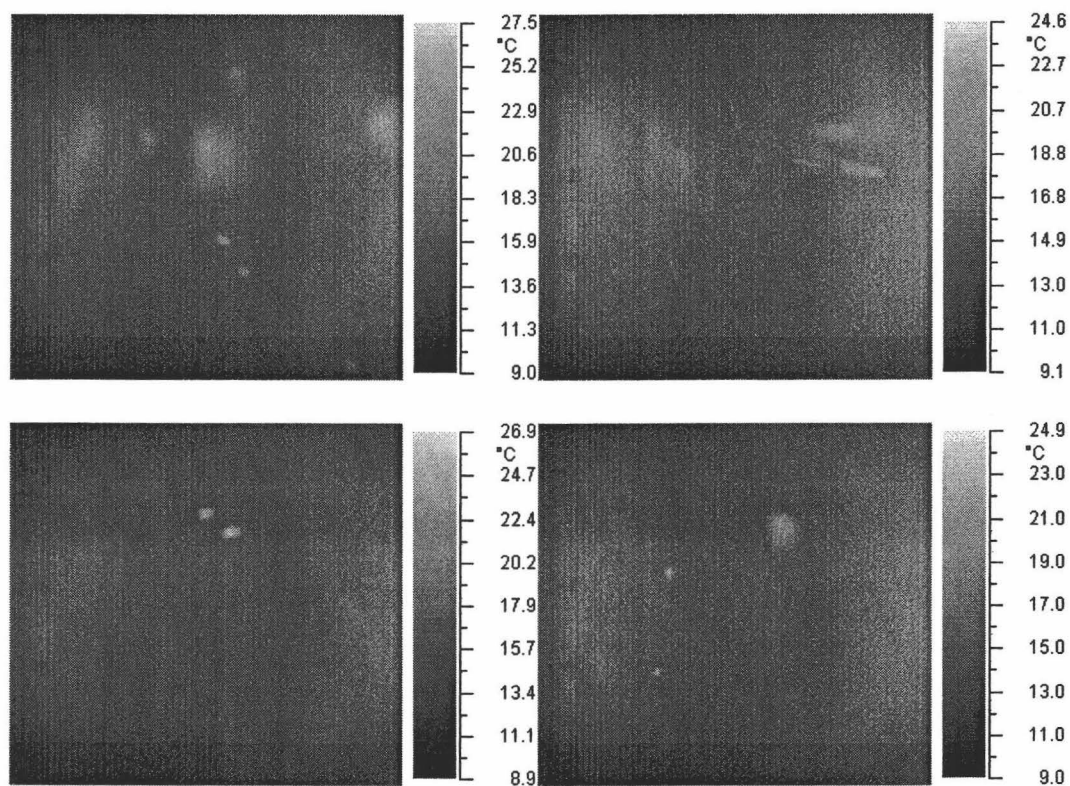


Figure E.17: Thermal visualization of 0.127 mm microchannel exit, 57.0 % LiBr, 7.04 W, 0.607 g/min, 0.0644 ms shutter speed.

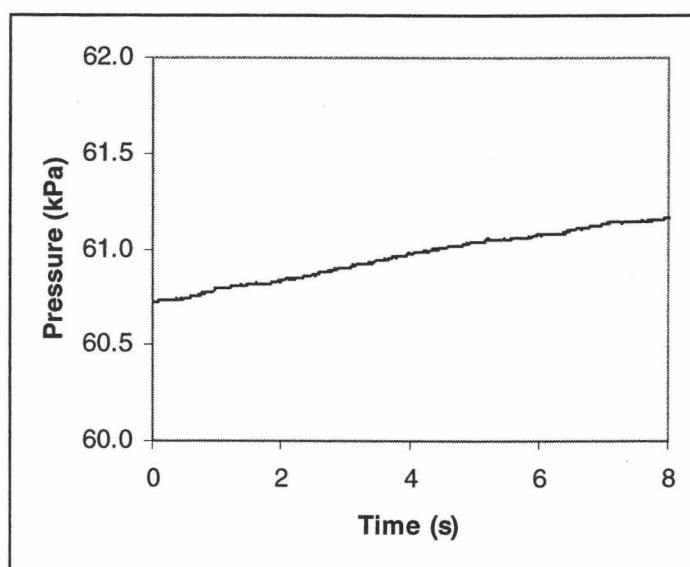
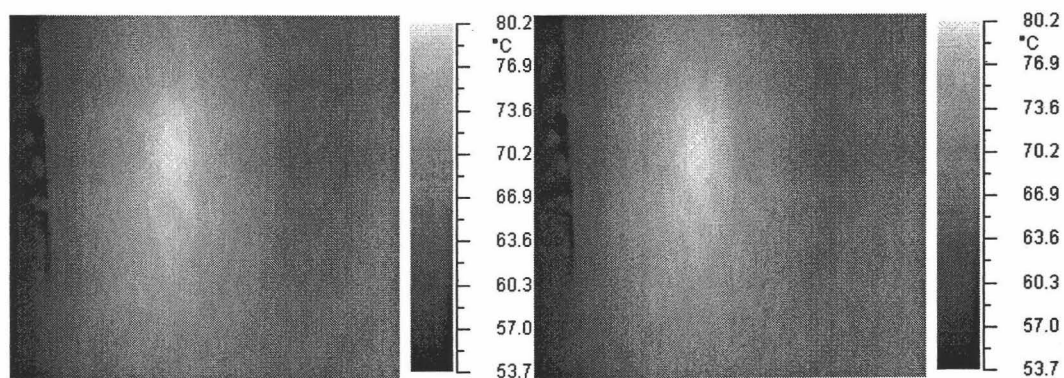
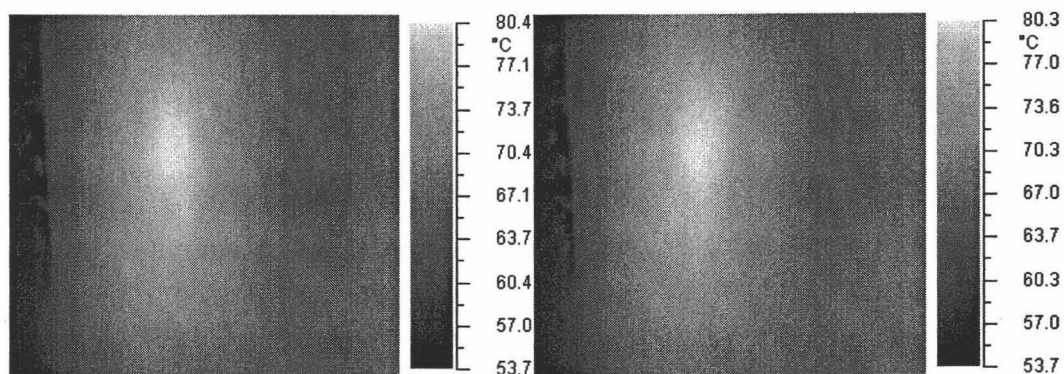
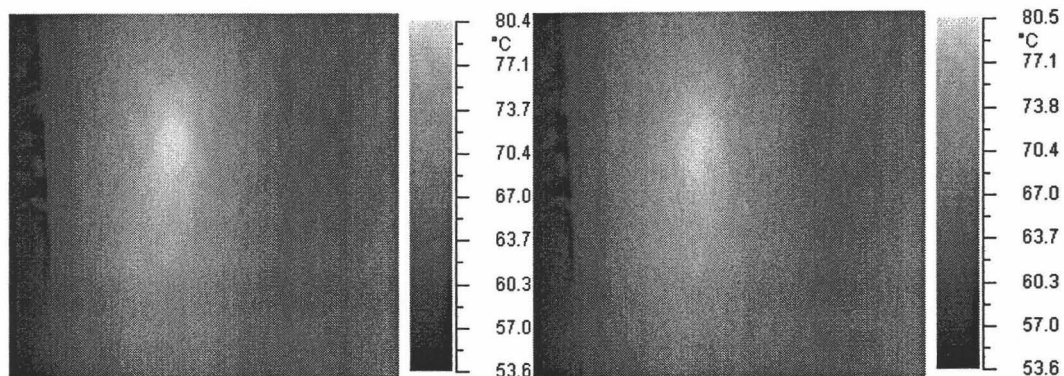


Figure E.18: Pressure response over 8 seconds at 100 Hz, single 0.127 mm channel, 7.04 W, 0.607 g/min, 57.0 % LiBr.

57.4 % LiBr, 4.98 W, 0.803 g/min



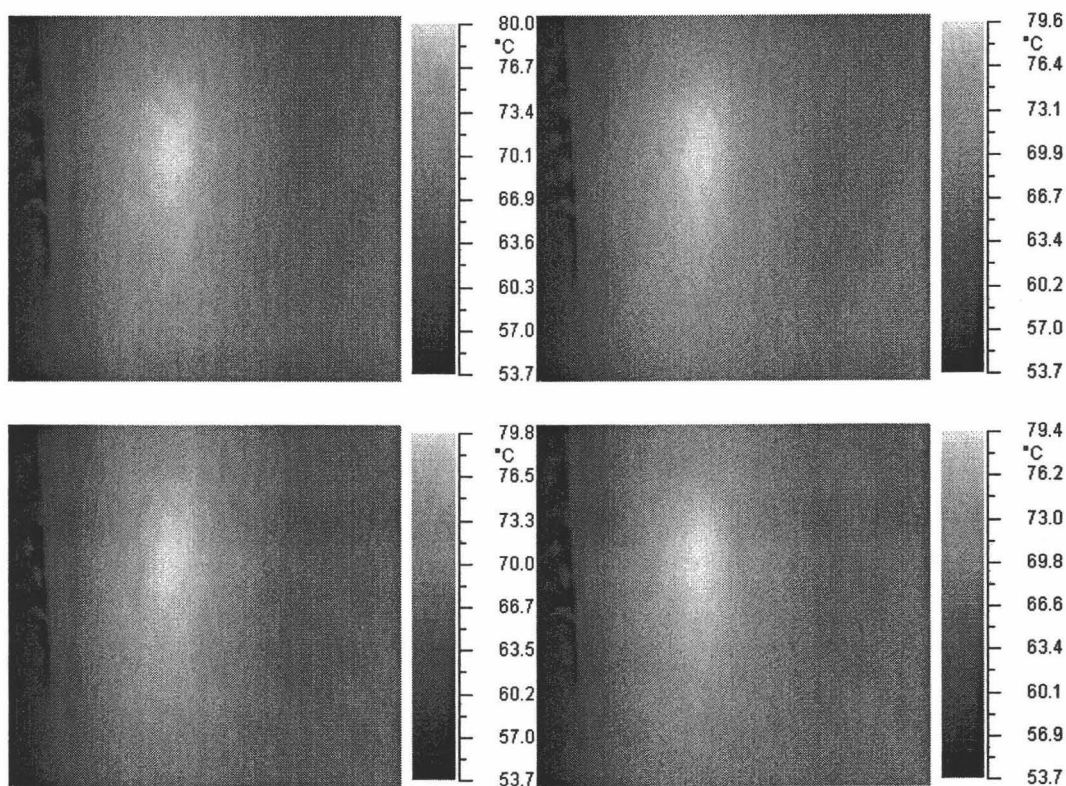


Figure E.19: Thermal visualization of 0.127 mm microchannel exit, 57.4 % LiBr, 4.98 W, 0.803 g/min, 1.256 ms shutter speed.

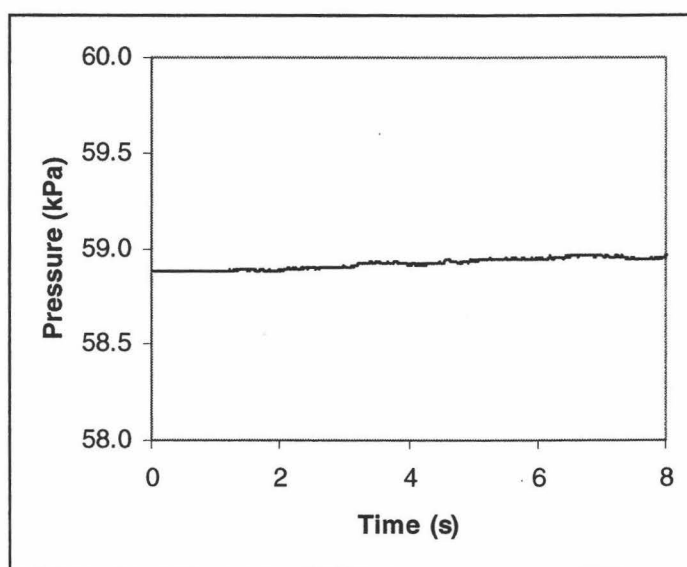
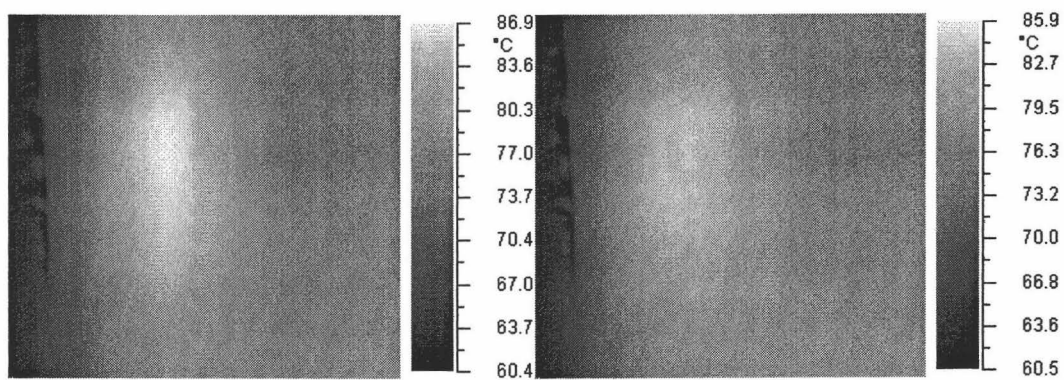
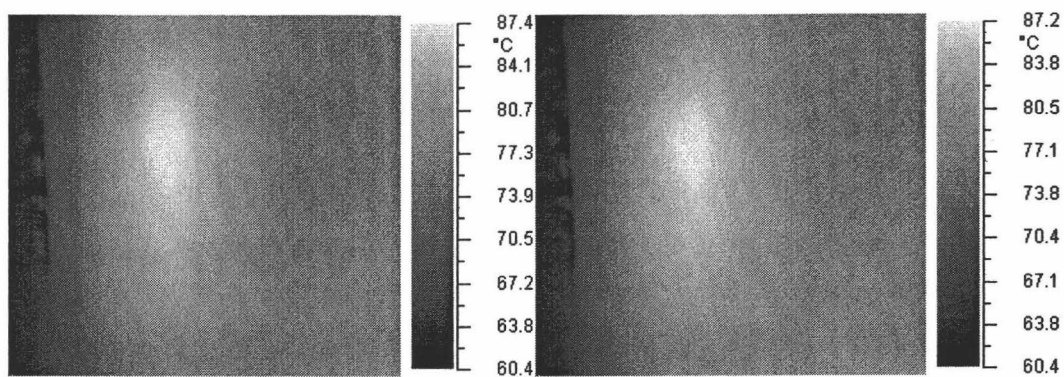
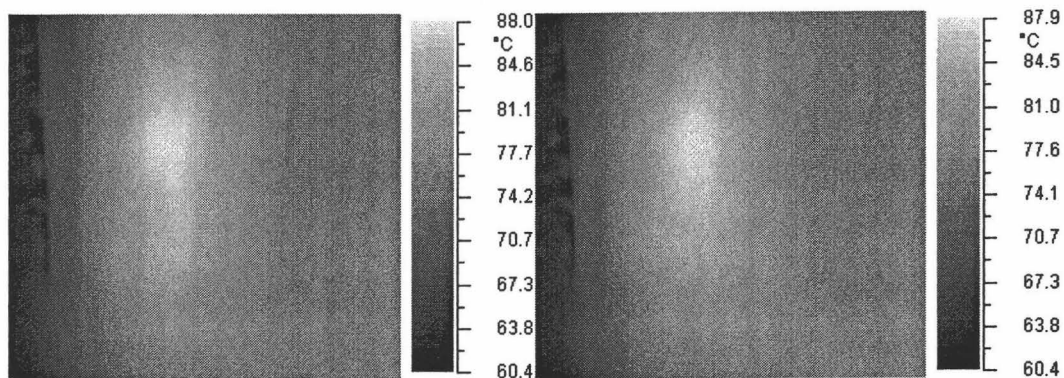


Figure E.20: Pressure response over 8 seconds at 100 Hz, single 0.127 mm channel, 4.98 W, 0.803 g/min, 57.4 % LiBr.

57.4 % LiBr, 5.96 W, 0.803 g/min



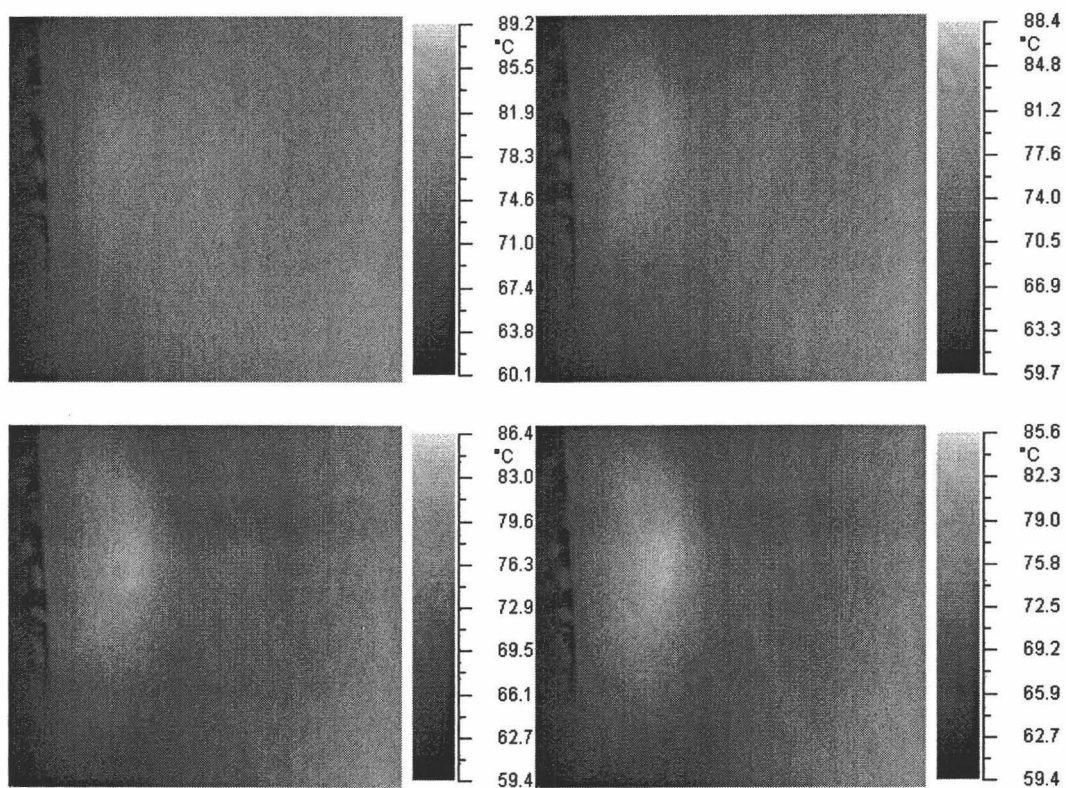


Figure E.21: Thermal visualization of 0.127 mm microchannel exit, 57.4 % LiBr, 5.96 W, 0.803 g/min, 1.256 ms shutter speed.

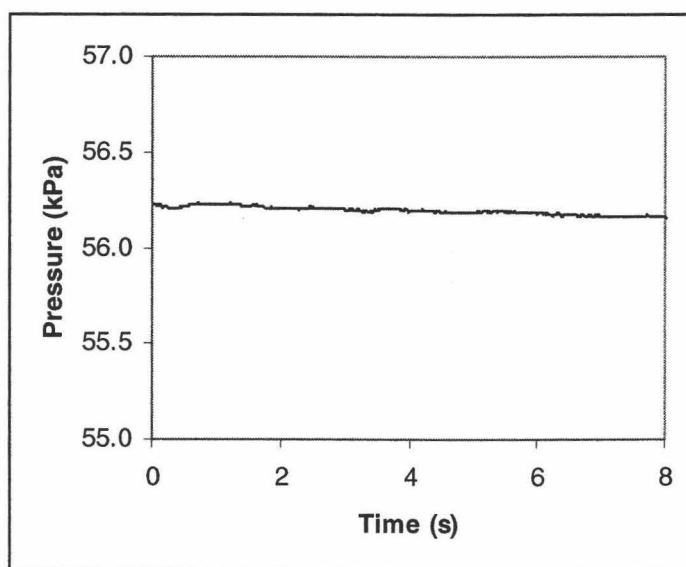
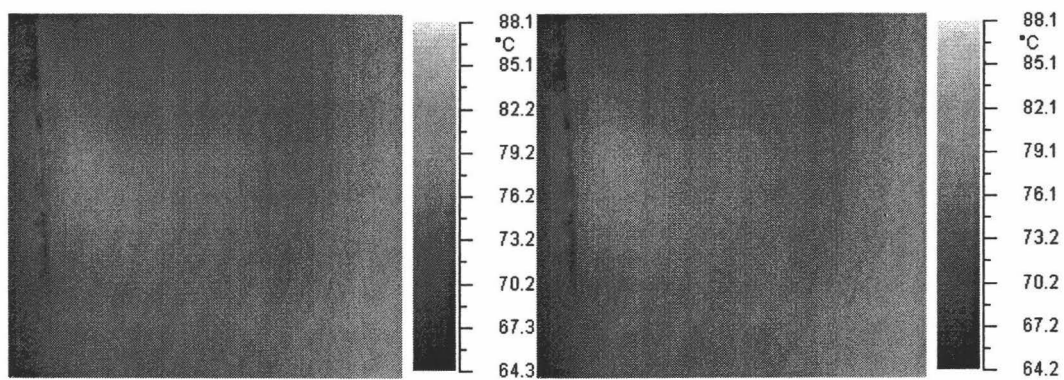
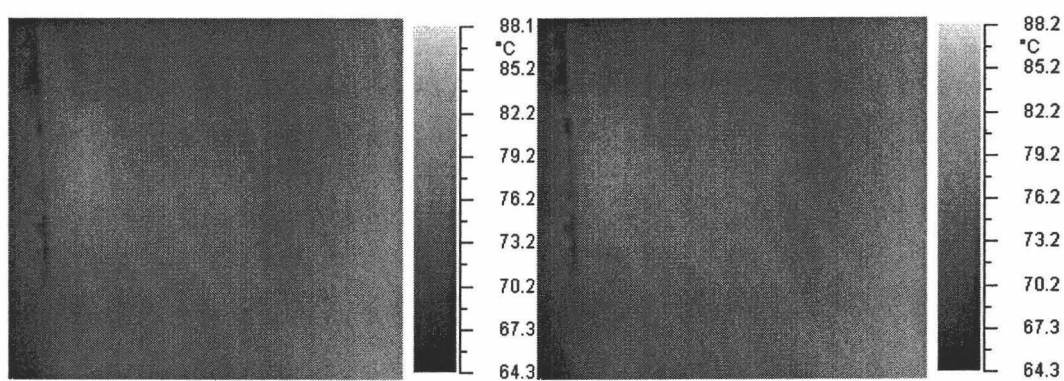
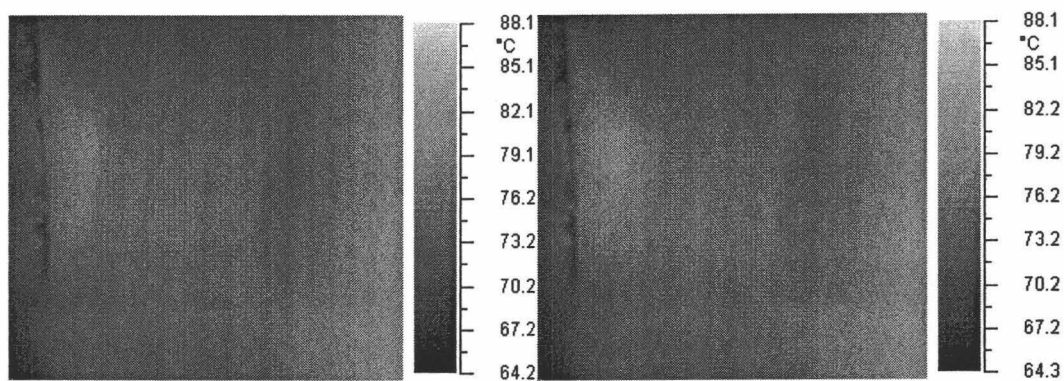


Figure E.22: Pressure response over 8 seconds at 100 Hz, single 0.127 mm channel, 5.96 W, 0.803 g/min, 57.4 % LiBr.

57.4 % LiBr, 7.04 W, 0.803 g/min



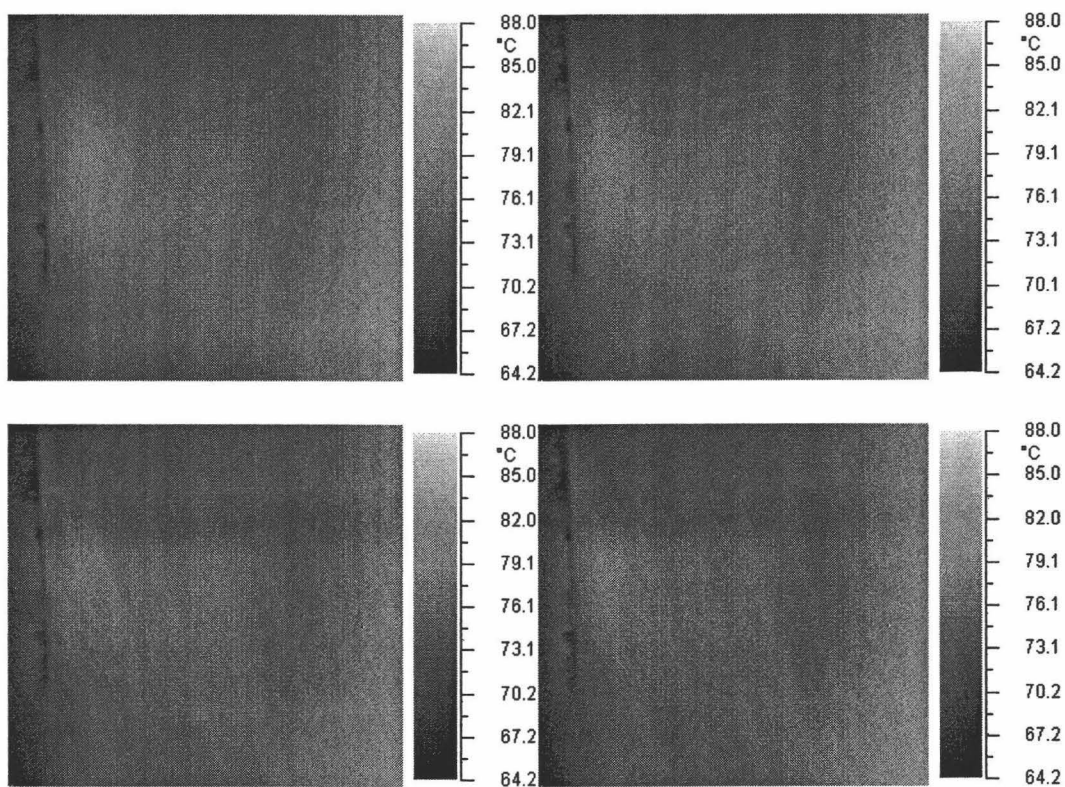


Figure E.23: Thermal visualization of 0.127 mm microchannel exit, 57.4 % LiBr, 7.04 W, 0.803 g/min, 1.256 ms shutter speed.

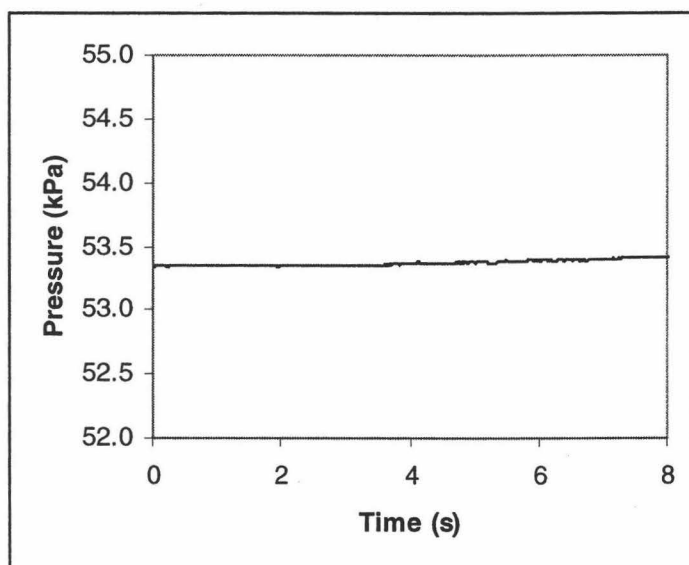


Figure E.22: Pressure response over 8 seconds at 100 Hz, single 0.127 mm channel, 7.04 W, 0.803 g/min, 57.4 % LiBr.

Appendix F: Manufacturing Drawings and LabVIEW Programs

Included part drawings:

Separation Chamber #3

Single Channel Desorber #2

Preheater #4

Included LabVIEW programs:

Data Acquisition and sub-VIs

Syringe Pump Control and sub-VIs