



Design and Development of Mini-Scale Refrigerator

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Abstract: Cooling for military, civilian and aviation applications and other electronic equipment has become an important issue. Many electronic systems, components, and processors create heat which must be effectively removed in order to ensure lower temperatures. Classical refrigeration using vapour compression has been widely applied over the last decades to large scale industrial systems. Now, the mini-scale (miniature) refrigerator using VCR seems to be an alternative solution for the electronic cooling problem. Fabrication of very small devices is now possible due to advances in technology. In this investigation a mini-scale refrigerator of 300W cooling capacity using R-134a as refrigerant is designed, built and tested. This test indicates that the actual COP of the developed system is 1.6 and second law efficiency is 19%. The experiments also show that the system was able to dissipate heat fluxes of 48 W/cm² and keep the junction (chip) temperature below 82 °C.

Keywords: Electronics cooling; Microchannels; Miniature refrigerator; Mesoscale refrigerator

I. Introduction

In the past decade, the performance of laptop, desktop, and server computers has dramatically improved due to miniaturization of Complementary Metal Oxide Semiconductor (CMOS) technology and faster clock rates. However, in order to meet this enhanced functionality and power consumption, heat dissipation rates, have also rapidly increased. It makes it increasingly difficult, or even impossible, to meet thermal management demands with either conventional air-cooling or non-chilled liquid cooling [1].

It has also long been known that microprocessor performance can be improved by lowering the junction temperature. Recently, Naeemi and Meindl [2] showed that, due to a decrease in leakage current at low temperature operation, a CMOS chip has the potential of achieving a 4.3x performance enhancement at -100 °C, compared to 85 °C operation, when operated in a power limited mode.

Vapour Compression Refrigeration (VCR) offers a practical means for removing large amounts of heat at sub-ambient temperatures and is a compelling technology to consider for increasing the performance and reliability of electronics [3]. After decades of development and extensive use in a wide range of applications, VCR systems have become very reliable and can be made sufficiently compact to fit in a desktop tower or a server rack. In fact, VCR is already used to directly cool computer and telecommunications equipment in some high performance applications [4]. IBM was the first to use refrigeration on high-end computing systems and developed a system that could remove 1050 W at 35 °C [3]. There are companies which are focusing on single-stage VCR systems designed to fit inside standard desktop towers. Two companies, for example, currently sell personal computer cooling systems using off-the-shelf VCR technology that can dissipate 200 W at -30 °C [5, 6]. To reach temperatures lower than about -50 °C, two or more single-stage VCR systems can be coupled in a cascade. Recently, a two-stage cascaded VCR system was demonstrated that could remove 100 W/cm² at a chip temperature of -63 °C [7].

Many researchers [8, 9, 10, and 11] have investigated refrigeration cooling of electronic systems. A number of studies have examined how miniature, often termed mesoscale refrigeration systems may be utilized for microelectronic cooling. Review of miniature VCR applications has been recently presented by Barbosa [12].

While VCR systems offer an attractive option for operating high-performance computers and large servers at sub-ambient temperatures, their size is still a concern for the engineer. Until VCR systems can be made compact enough to easily integrate into electronics packages, widespread application of refrigeration in electronic cooling will remain limited [1].

The main problem in building a small VCR system was an affordable miniature compressor in the fractional kilowatt range and that would fit in a small space. However in this investigation, the components like a microchannel evaporator, and a microchannel condenser for a mini scale refrigerator was developed and a commercially available compressor was used. The performance of a mini scale refrigerator with optimum matching parameters was tested. This system is smaller than a conventional system by at least an order of magnitude and larger than newly proposed micro-scale systems by a few orders of magnitude. Unlike conventional systems, this refrigerator is developed by microelectronic fabrication techniques (evaporator/condenser) and also it was assured that such a system can be reproduced with cost cutting for different future requirements like microelectronic cooling

systems, portable cooling systems, avionic applications and other high density cooling systems.

Nomenclature

COP:	Coefficient of performance
H:	Height (m)
I:	Current (Amp)
L:	Length (m)
m:	Mass flow rate (gm/sec)
N:	Number
P:	Pressure (Bar)
Q:	Heat (W)
t:	Thickness (m)
T:	Temperature ($^{\circ}\text{C}$)
V:	Voltage (Volt)
W:	Width/Work (m/W)

Subscript

act:	Actual
c:	Compressor
cap:	Capillary
CFM:	Cubic feet per minutes
Con:	Condensor
Ch:	Channel
evp:	Evaporator
I:	In
IC:	Integrated circuit
Is:	Isentropic
o:	Out
Sub:	Subcooled
Sup:	Superheated
Syst:	System
th:	Thermal
Th:	Theorotical
Ref:	Refrigerant
wb:	Wall base

Greek symbols

η :	Efficiency
Δ :	Change

II. Conceptual mini-scale vapour compression refrigeration system

The major function of a refrigerator is to create a cold region by rejecting heat to the ambient. A simple vapour compression system consists of a miniature compressor, air cooled condenser, expansion device and micro channel evaporator. Due to the requirement of miniaturization and overall reduced size a refrigeration system is hereby proposed with a micro channel heat exchanger (Evaporator and condenser) and small scale compressor. Figure 2.1 shows the basic components of a vapour compression system.

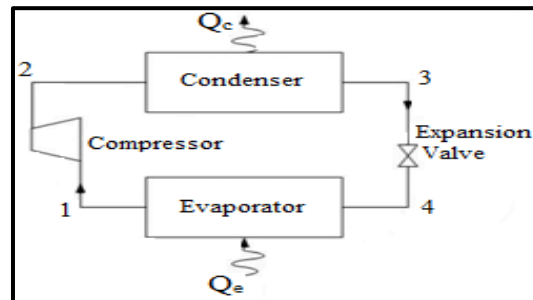


Figure 2.1- Basic Components of a Vapour Compression System

As shown in the figure an evaporator is placed in thermal communication with a micro electronic component i.e. IC chip. Refrigerant is circulated to the system through a micro channel evaporator in which heat generated by the electronic component is transferred to the cooling system. This heat generated by the component is transferred to the evaporator by thermal conduction. The thermal resistance between Evaporator and component would be minimized by applying thermal paste at the interface of component and evaporator. Heat absorbed by the evaporator vapourizes the refrigerant circulating through the evaporator, and the resulting vapour is compressed by the compressor using external work. Compressed vapour is transferred to the condenser where heat is rejected to the atmosphere by forced convection provided by fan air. In the condenser phase change i.e. gas to liquid takes place due to rejection of heat. The resulting liquid then passes through a throttling element through the evaporator thereby completing the refrigeration cycle.

III. System Layout, Design and Components Selection

A. Refrigeration system layout

A schematic diagram of the Mini-scale refrigeration system is shown in Fig.3.1. This system operates on a conventional vapour compression cycle. Various components and their locations are as shown in the figure. This system needs a commercially available small size compressor, a micro channel condenser, capillary tube for expansion purposes, micro channel evaporator, a fan for a condenser, and a heat source which simulates the microprocessor chip as the main components. The evaporator is incorporated with a cartridge heater whose power can be varied and thus it is possible to vary the input heat Q_{evp} to the evaporator. Further we have used a

number of thermocouples and pressure gauges at different locations denoted by 'T' and 'P' in the diagram. For experimental investigation of the system, readings of various system parameters have been obtained using these temperature and pressure sensors. For measurement of flow a rotameter is used. A voltmeter and ammeter measure the power to compressor. Further shut off valves are placed before and after the evaporator to shut off the flow of refrigerant in case of any damage or for replacement of the evaporator.

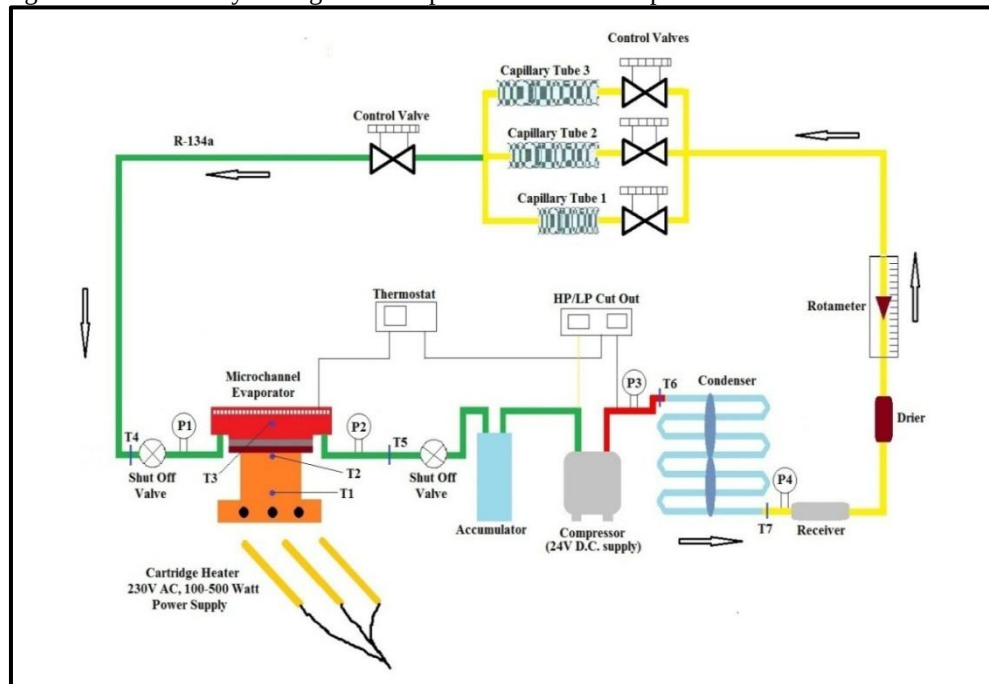


Figure 3.1- General Layout of Mini-scale Refrigerator

B. Refrigeration cycle

The refrigeration cycle is designed for this mini refrigerator using software Cool pack [13]. The following conditions were assumed for the cycle. Input heat $Q_{evp} = 300W$, evaporator temperature $T_{evp} = 10^{\circ}C$, Condenser temperature $T_{con} = 50^{\circ}C$, Superheating of $12^{\circ}C$, sub cooling of $3^{\circ}C$ and assumed isentropic efficiency of 70%. Figure 3.2 shows the cycle and its parameters on coolpack. The values computed by this software are given in table 3.1.

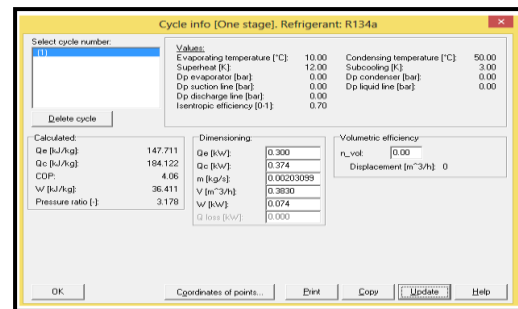
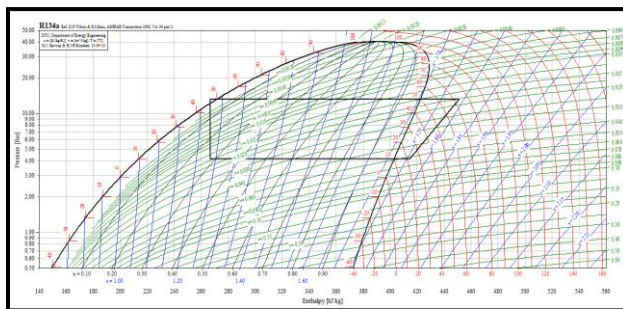


Figure 3.2 Vapour Compression Cycle Plot Using Cool Pack [11]

Table 3.1 Cool Pack Software results

Power consumption by compressor (W)	P_{comp}	74
Heat rejected by condenser (W)	Q_{Con}	374
Refrigerant circulated (gm/sec)	$\dot{m}$	2.03
Refrigerant volume flow rate (m^3/hr)	V_o	0.383
Coefficient of performance	COP	4.0
Compression ratio	p_r	3.178

C. Components selection

As per design requirement, commercial availability and manufacturing feasibility component required for this mini scale refrigerator was selected.

1. **Compressor:** The compressor is used to transfer gaseous R-134a from evaporator to the condenser increasing its temperature and pressure. In this study reciprocating compressor was selected as specified in Table 3.2.

Table 3.2 Specification of compressor

Mass flow rate of refrigerant, m (gm/sec)	Compression ratio	RPM	Compression displacement (cm ³)	No. of stages	Refrigerant
2.00	3.18	2500	2.5	Single	R 134 a

On the basis of system parameters such as refrigerant mass flow rate, pressure, temperature ranges, applications and market survey considering availability, durability and cost factor a model BD 250GH from Danfoss was selected.

2. **Condenser**

For this system a micro channel condenser is selected having a maximum heat rejection capacity of 700W and with overall dimensions of 114mm × 119mm × 20mm. A 12V DC fan is used as a condenser fan which gives a maximum flow rate of 105 CFM. Design parameters of the microchannel condenser are shown in Table 3.3.

Table 3.3 - Parameters of Micro channel Condenser

Parameter	Value
Channel width (mm)	0.7
Channel depth (mm)	1.2
Channel Wall thickness (mm)	0.22
Channel Numbers	16
Fin Width (mm)	16
Fin Height (mm)	8
Overall length (mm)	140
Overall height (mm)	119
Overall width (mm)	20
Fins/inch	21

3. **Heat Source**

The heat source consists of a cubical copper block with dimensions of 25mm on a side. Three cartridge heaters were mounted into the base underneath the copper block and controlled with an input power of up to 300 W provided. The copper block-evaporator interface was improved with the thermal conductive paste as shown in Figure 3.3.

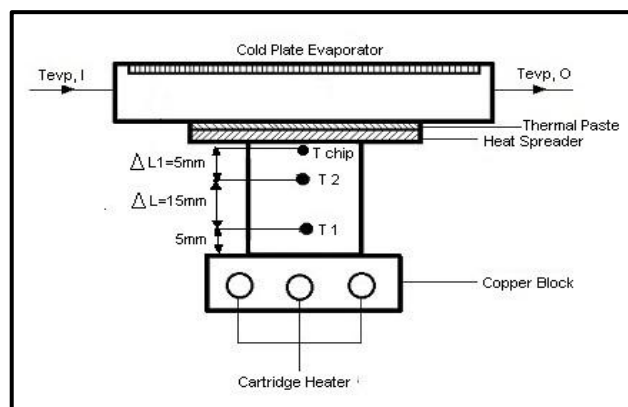


Fig 3.3 Copper block with cartridge heater and thermocouples

4. **Capillary Tube**

In this experiment the expansion device is a capillary tube of selected ID and design length with hand-operated needle valves. Experiments with ID 0.8 mm, and design length 850 mm capillary tube and respective flow rates experimentations were performed.

5. **Evaporator**

The evaporator or cold plate is designed [14] to absorb heat from the heat dissipating unit (cartridge heater) as shown if figure 3.3 which has a capacity of 300 W. An evaporator for removal of 300 W of heat is designed. The width of the channel and height was selected as 0.8 mm and 2.3 mm as per manufacturing feasibility and other parameters were designed as shown in Table 3.4. In this investigation, the evaporator is designed to be in direct contact with the heat dissipating unit.

Table 3.4 - Design parameters of mini/microchannel evaporator

Height of Channel $H_{ch}(mm)$	Width of Channel $W_{ch}(mm)$	Thickness of Channel (wall thickness) $t_{ch}(mm)$	Number of Channels, N	Length of channel $L_{ch}(mm)$
2.3	0.8	0.5	41	58

6. Other components

Thermocouples and pressure transducers were installed on the refrigerant side at the inlet and outlet of compressor, condenser, expansion device and evaporator to determine the refrigerant state points. The power input to the cartridge heaters in the copper block was measured by a Watt meter, while heat input to the evaporator was determined from a row of three thermocouples installed in the copper block in the direction of heat flow as shown in Figure 3.3.

IV. Experimental Setup, Observations and Results

After the design and development of the mini-scale refrigeration system as shown in Figures 4.1 a and b, the observations were made during a number of trials and the average readings were studied as shown in Table 4.1. The experimental results obtained after calculations are summarized in Table 4.2.

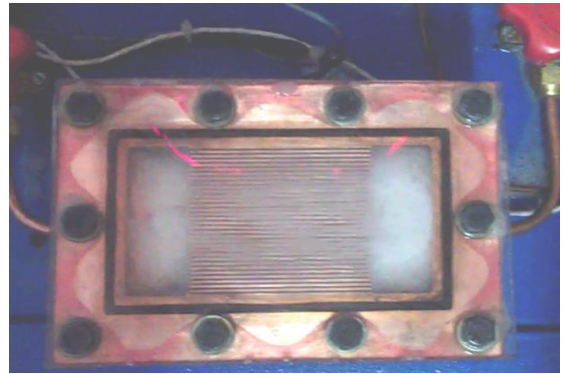
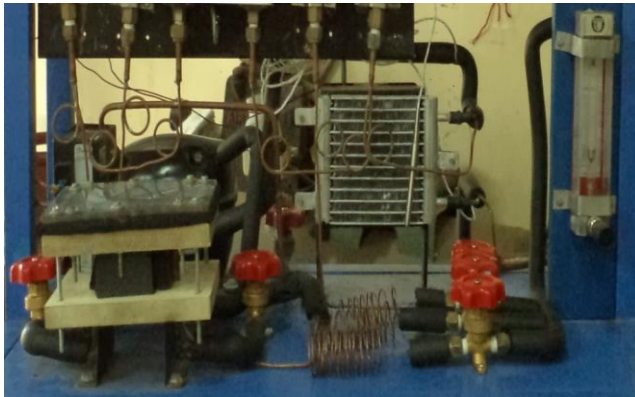


Figure 4.1 (a) Developed Mini-Scale Refrigeration System, (b)Flow through microchannel evaporator.

Table 4.1 Experimental observations

Q(w)	L _{cap} (mm)	T _{evp}	T _{cond}	T _{sup}	T _{sub}	m	T1	T2	T3	T4	T5	T6	T7	T _{wb}	P1	P2	P3	P4	V	I	CFM	T _{cond} air in	T _{cond} air out
300	850	16	50	10	2	3.1	105	89	26	25	26	53	49	25	77	67	190	190	24	7.8	105	27	38

Table 4.2 Experimental Results

Parameter	Notation	Value
Heat input to evaporator by cartridge heater	Q_{CPU}	300 W
Refrigerant side cooling capacity	Q_{evp}	260 W
Condenser Side Heat Rejection (Refrigerant Side)	$Q_{c,ref}$	543 W
Condenser Side Heat Rejection (Air Side)	$Q_{c,air}$	645 W
Theoretical Work of Compression	W_c	85 W
Electric Power Consumption	W_{elec}	186 W
Theoretical COP	COP_{Th}	3.5
Actual COP	COP_{act}	1.6
Overall Isentropic Efficiency	$\eta_{o,is}$	45 %
Second Law Efficiency	η_{II}	19 %
Chip Temperature	T_{chip}	82°C
Evaporator- Heat Spreader Thermal Resistance	$R_{th,evp}$	0.223 K/W
Overall System Resistance	$R_{th,syst}$	0.189 K/W

V. Results and Discussion

After design and development of the system, the performance was measured under the following operating conditions: Evaporator temperature of 16°C; refrigerant superheat at the compressor inlet of 10° C; condenser temperature of 50° C; refrigerant sub cooling temperature at the condenser outlet of 4° C; and ambient air temperatures of 27° C.

The energy balance of the evaporator was within 15%. The measured refrigerant side cooling capacity was lower than the measured heat transfer from the cartridge heater (predicted CPU). The reason for this was the heat losses from the copper block/heat spreader through the insulation to the ambient air and measurement uncertainty. The energy balance of condenser was within 15%. This is due to inaccuracy in determining the air flow rates. The compressor used in this study was not designed for the given application and its measured isentropic efficiency was 45%. This efficiency can be improved by selecting a reliable compressor.

The theoretical value of COP was found to be 4 which assumes that heat given by the simulated chip completely reached the evaporator base. But the actual COP of the cycle was found to be 1.6. This is due to the fact that the heat given by the simulated chip suffered loss due to radiation and convection irrespective of the insulation. Also there was more consumption of electric power by the compressor to achieve the given refrigerating effect than the theoretically calculated one which results in the lower COP of the system. The COP of the system can be improved by using a well design compressor and more effective insulation which reduces heat losses from the evaporator to the atmosphere. The second law efficiency of the system was obtained as 19%. If this is compared to household refrigerator the loss is attributed to the irreversibility of the compressor.

When the heat load was 300 W, 2500 rpm the compressor speed, 200 gm the refrigerant charge, 3 gm/sec the refrigerant flow rate, 850 mm the capillary tube length, the predicted chip temperature (T_3) was maintained at 85 °C and the temperature 3.7 mm below the channel wall was maintained at 26° C. The time required for the system to reach thermal equilibrium was about 5-8 minutes.

The experimentally determined Evaporator-heat spreader thermal resistance was 0.223 K/Watt. The thermal resistance can be further minimized by improving the interference contact conductance in the experimental system. The overall system thermal resistance was 0.189 K/Watt.

VI. Conclusion

A mini-scale vapour compression refrigeration system of 300 Watt cooling capacity using R134a as a refrigerant was designed, built and tested. This system includes a commercial miniature compressor, capillary tubes, a custom-made condenser and cold plate i.e. micro channel evaporator. The experimental results show that the system was able to dissipate CPU heat fluxes of approximately 48 W/cm² and keeps the junction temperature (Predicted chip) below 82 °C for a chip size of 25X25 mm². After extensive experimental investigation, the main energy losses occurring in the condenser, evaporator and compressor were highlighted. The experimental results also indicate that the compression ratio of the compressor was 3 and the coefficient of performance of the developed system was 1.6 with second law efficiency of 19%. The refrigerant charge quantity was 200 gm and the optimal capillary tube length was 850 mm.

VII. References

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