Development, Study, and Testing of Small-Scale Refrigeration System for Electronics Cooling Using Cold Plate Evaporators

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Abstract

A small-scale refrigeration system (SSRS) for electronics cooling was designed, developed, and tested. The refrigeration system consisted of four major components: a compressor, a mini-channel condenser, an expansion valve, and a mini-channel cold plate evaporator. The effects of the mini-channel evaporator dimensions and the channel numbers on the efficiency of the small-scale refrigeration system were studied. Three different channel dimensions of the cold plate evaporator were tested. The cold plate evaporator had a refrigerant-side cooling area of 1650 mm^2. The hydraulic diameters of Evaporator 1, 2, and 3 were of 1.075 mm, 1.253 mm, and 2.151 mm, respectively. The channel number of Evaporator 1, 2, and 3 were 27, 27, and 18, respectively. The refrigerant mass flow rates were varied from 1.175-1.596 g/s, the refrigerant suction and discharge pressures of R-134a were 143-360 kPa and 760-1220 kPa, respectively. The compressor speed was between 4500 and 5500 rpm, the inlet air temperature of condenser was from 23 to 29°C, and the heater input powers of the simulated electronics were ranged from 200-310 W.

From the test results at heat dissipation of 200 W, the overall system Coefficient of Performance (COP) of Evaporator 2 were higher than those of Evaporator 1 and Evaporator 3 by 2.60-9.80% and 7.38-12.50%, respectively. While, the evaporator thermal resistances of Evaporator 2 are lower than those of Evaporator 1 and Evaporator 3 by 38.70-50.02% and 37.04-50.92%, respectively. The evaporator and overall system thermal resistances of Evaporator 2 are ranged from 0.3803 to 04107 K-cm^2/W and from -0.1071 to -0.2646 K-cm^2/W, respectively. The experimental results indicated that Evaporator 2 with a hydraulic diameter of 1.253 mm and aspect ratio of 5.06 had the best performance because of higher condenser effectiveness and overall system COP and lower evaporator and overall system thermal resistances.

***Keywords**:* electronics cooling, refrigeration system, cold plate evaporator.

Nomenclature

k	Conduction heat transfer coefficient , (W/m°C)
COP	Coefficient of performance, (-)
h	Enthalpy, (J/kg-K)
$\dot{m}$	Mass flow rate, (kg/s)
$\dot{Q}$	Heat loss or heat transfer, (W)
P	Pressure, (Pa)
R	Thermal resistance, (K/W)
T	Temperature, (°C)
W	Power input, (W)
$\dot{\forall}$	Volume flow rate, (m^3/s)

Greek symbols

ε	Heat exchanger effectiveness, (%)
η	Efficiency, (%)
ρ	Density, (kg/m^3)

Subscripts

a	Ambient air or air
comp	Compressor
cond	Condenser
evap	Evaporator
i	Inlet , inner
max	Maximum
o	Outlet or overall
r	Refrigerant
s	Isentropic
sys	System
th	Thermal
tot	Total

1. Introduction

In these recent decades, the computer development has been very rapid. This development is accompanied with the increase of heat dissipation and the miniaturization of the computer chips. The International Technology Roadmap for Semiconductors [1] the maximum heat dissipation from a single chip package will rise to 525 W (75 W/cm^2) in 2014 for high-performance systems. Meanwhile, the maximum junction temperature must continue to be maintained at or below 80°C in 2014.

The cooling methods, such as heat sink and heat pipe, [2, 3] are widely used nowadays. These methods are aimed at fast dissipating heat and hence their cooling capabilities are limited. It is estimated that as the chip power reaches 180 W, the conventional cooling methods would become incompetent [4]. Therefore, new active cooling methods are needed.

From the experiments of various active cooling approaches [5], such as the vapor compression refrigeration system [6], the thermoelectric refrigeration and pulse tube, are compared. Several problems are not resolved including heat capacity, efficiency, reliability, size and cost. However, it is believed that among all these methods, the vapor compression refrigeration is the best.

From the previous studies, there is a development of the small-scale refrigeration in order to decrease the chip surface temperature by using a cold plate evaporator. However, it has not been the experiments on the mini-channel cold plate evaporator to study the effect of channel dimensions on the efficiency of the small-scale refrigeration. Therefore, the study of cold plate evaporator dimensions will be performed to observe the differences on the chip surface temperature and effectiveness. The

experiments are designed by using three different evaporators and the COPs are calculated and compared for the most efficient cold plate evaporator.

2. Experimental setup

A small-scale refrigeration system for electronics cooling as shown in Fig. 1 was designed, constructed, and tested at various operating conditions. The system consists of five main components: a copper block to simulate the heat from the chip, a mini-channel cold plate evaporator, a small-scale compressor, a mini-channel condenser, and an expansion device. The brushless DC compressor is a variable-speed compressor with 20-30 V power input and includes an inverter to vary the speed from 2000 to 6500 rpm. The swept volume of the rotary compressor is 1.4 cm^3/revolution. A serpentine condenser had surface area equal to 20x18 cm^2 and thickness of 5.5 cm. A needle metering valve was used as the expansion device.

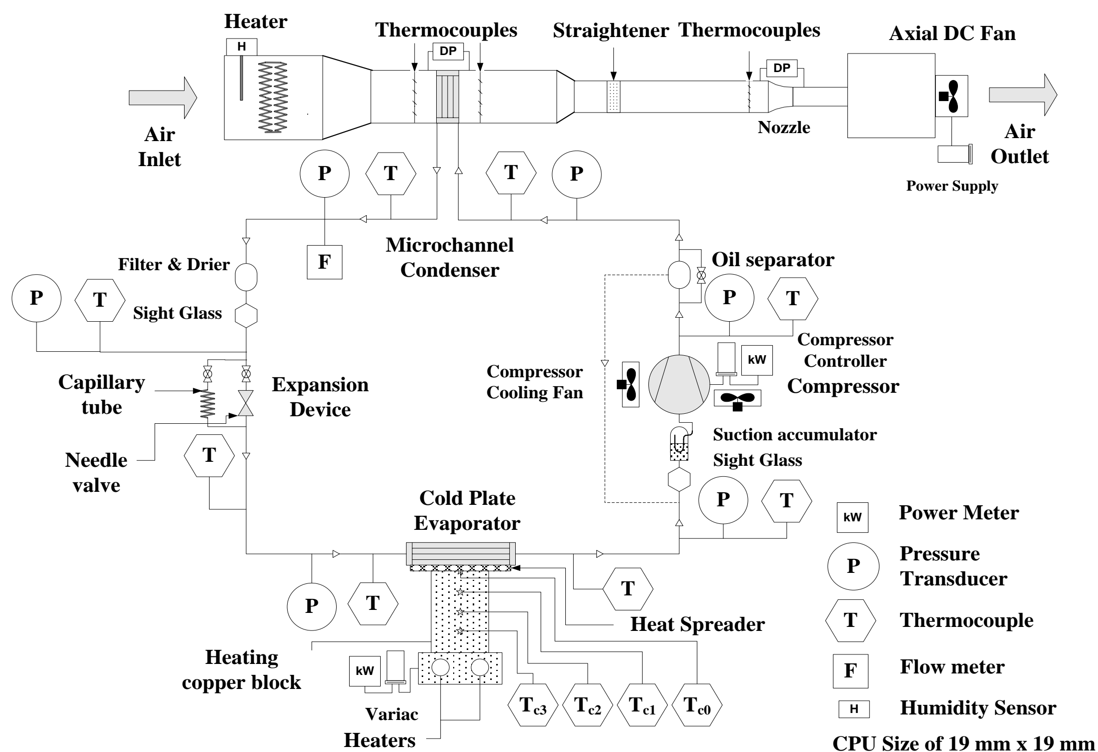

Fig. 1 Schematic of the SSRS system

Three thermocouples and three cartridge heaters of 150 W were inserted into the copper block with dimensions of 20 mm on a side. The cold plate evaporator included a mini-channel heat exchanger integrated with a heat spreader distributed the heat from the small copper block surface to the large heat exchanger surface. Three cold plate evaporators were tested in this study. The detail dimensions of the evaporators are shown in Table. 1.

The condenser was installed in a wind tunnel according to ANSI/ASHREA 41.2-1987 Standard [7]. Temperatures and pressures were used to measure both on air- and refrigerant-sides. All temperature measurements were T-type thermocouples. Differential pressure

transmitters were installed on the air-side across a condenser and a nozzle. The condenser air flow rate was determined from the measured pressure drop of a nozzle. For the refrigerant-side, a high pressure transducer ranged from 0 to 25 bar was installed at the outlet of the condenser and a low pressure transducer ranged from 0 to 16 bar was installed at the inlet of the evaporator. Two differential pressure transmitters were installed on the refrigerant-side across the condenser and evaporator for pressure drop measurement. The coriolis mass flow meter was installed between the condenser and needle valve.

A data acquisition system from Agilent VEE was used in combination with a computer to collect and record all measurement data. During the tests, the outputs were displayed on the computer screen for monitoring.

Table. 1 Detail dimensions of cold plate evaporators

Evaporator	1	2	3
1. Area of Channels, (mm^2)	1,650	1,650	1,650
2. Total area of cold plate evaporator, (mm^2)	2475	2475	2475
3. Evaporator base thickness, (mm)	10	10	10
4. Number of Channels, (-)	27	27	18
5. Hydraulic diameter, (mm)	1.075	1.253	2.151
6. Channels depth, (mm)	1.90	3.80	3.80
7. Fin width, (mm)	0.75	0.75	0.75
8. Channels width, (mm)	0.75	0.75	1.50
9. Aspect ratio (depth/width)	2.53	5.06	2.53

3. Data reduction

The heat dissipation rate from the copper block to the cold plate evaporator was calculated from the axial heat conduction in the copper block:

$$\dot{Q}_{CPU} = \frac{k_{copper} A_c}{L_{c1-c3}} \left(T_{c3} - T_{c1} \right) \quad (1)$$

where, T_{c1} and T_{c3} is the temperatures at the top and bottom positions in the copper block. L_{c1-c3} is the distance between the top and bottom thermocouples in the copper block as shown in Fig. 1. The thermal conductive paste were used between the copper block and cold plate evaporator interfaces.

The cooling capacity of the refrigeration system was calculated by multiplying the refrigerant mass flow rate with the refrigerant enthalpy difference across the evaporator:

$$\dot{Q}_{evap,r} = \dot{m}_r \left(h_{evap,o} - h_{evap,i} \right) \quad (2)$$

From the measurements of the refrigerant outlet pressure and temperature in the single-phase superheat region, the outlet evaporator enthalpy. The evaporator inlet enthalpy was obtained by assuming an isenthalpic process across the expansion device.

Similarly, the refrigerant-side heat rejection rate of the condenser was calculated by multiplying the refrigerant mass flow rate with the refrigerant enthalpy difference across the condenser:

$$\dot{Q}_{cond,r} = \dot{m}_r \left(h_{cond,i} - h_{cond,o} \right) \quad (3)$$

The air-side heat rejection rate of the condenser was determined as the product of the air volume flow rate measured at the nozzle, the air density, and the air-side enthalpy difference across the condenser:

$$\dot{Q}_{cond,air} = \dot{\forall}_{air} \rho_{air} \left(h_{cond,air,o} - h_{cond,air,i} \right) \quad (4)$$

The Coefficient of Performance (COP) of the refrigeration cycle and the COP of the overall system as follows:

$$COP_{refrig} = \frac{\dot{Q}_{evap,r}}{\dot{W}_{comp,r}} \qquad (5)$$

$$COP_{sys} = \frac{\dot{Q}_{evap,r}}{\dot{W}_{comp,e}} \qquad (6)$$

where the refrigerant compression work and overall system work can be obtained by:

$$\dot{W}_{comp,r} = \dot{m}_r \left(h_{comp,o} - h_{comp,i} \right) \qquad (7)$$

The condenser effectiveness was defined as the ratio between the air-side heat rejection rate and the maximum heat rejection rate of condenser:

$$\varepsilon_{cond} = \frac{\dot{Q}_{cond,a}}{\dot{Q}_{cond,\max}} \qquad (8)$$

where the maximum heat rejection rate was:

$$\dot{Q}_{cond,\max} = \dot{m}_{air} c_{air} \left(T_{sat@P=P_{cond,i}} - T_{air,i} \right) \qquad (9)$$

The performance of the cold plate evaporator was defined by the cold plate evaporator thermal resistance:

$$R_{th,evap} = \frac{T_{chip} - T_{evap}}{\dot{Q}_{evap,r}} \qquad (10)$$

where T_{chip} is the chip surface temperature obtained by linear extrapolation from three thermocouples in the copper block.

Similarly, the overall system thermal resistance was defined as the ratio of the difference between the chip surface temperature and the condenser air inlet temperatures to the chip heat dissipation rate:

$$R_{th,sys} = \frac{T_{chip} - T_{cond,air,i}}{\dot{Q}_{CPU}} \qquad (11)$$

4. Results and Discussion

The experiments were conducted for a condenser air inlet temperature of 24-30°C and a condenser air flow rate of 0.078 kg/s by varying two parameters: CPU heat dissipation rates between 200 and 310 W; and compressor speeds from 4500 to 5500 as shown in Table. 2. The effects of two parameters on the chip heat dissipation rate, the refrigeration cooling capacity, the condenser effectiveness, the evaporator and overall system thermal resistances, and the overall system Coefficient of Performances (COPs) are investigated for three cold plate evaporators.

Table. 2 Test matrixes.

Test	Q_{CPU} (W)	N_{comp} (RPM)
1	199.5	4500
2	199.5	5000
3	199.5	5500
4	252.0	4500
5	252.0	5000
6	252.0	5500
7	310.5	4500
8	310.5	5000
9	310.5	5500

Table. 3 illustrated the measuring data for Evaporator 1. The performance results were calculated based on the measuring of refrigerant-side temperatures and pressures, refrigerant mass flow rate, and copper block temperatures. Measurements from the present experiments also showed that the refrigeration system can maintain the chip surface

temperatures ranged from 40°C to 50°C, which are below 80°C criteria of ITRS [1].

Table. 3 Measuring data for Evaporator 1.

Test	$T_{comp,o}$ [°C]	$T_{evap,o}$ [°C]	T_{CPU} [°C]	P_{evap} [kPa]	P_{cond} [kPa]	$\dot{m}_r$ [g/s]
1	40.56	9.58	43.72	326	865	1.175
2	42.97	9.00	40.90	316	934	1.249
3	47.22	8.87	40.99	316	1062	1.288
4	43.66	11.99	49.74	360	954	1.206
5	47.58	11.57	48.47	354	1074	1.268
6	46.63	-2.41	36.47	153	1021	1.458
7	46.83	2.04	45.53	195	1029	1.404
8	47.46	0.40	42.57	176	1046	1.425
9	48.00	-1.38	39.76	163	1066	1.510

From the calculations by using the equations in the data reduction part, the chip surface temperature, the cooling capacity, the condenser effectiveness, the evaporator and overall system thermal resistances are calculated and shown in Table. 4. The results of Evaporator 2 and 3 are determined by the same approaches of Evaporator 1.

Table. 4 Data for Evaporator 1.

Test	T_{chip} [°C]	$\dot{Q}evap$ (W)	ε_{cond} (W)	$R_{th,evap}$ [K-cm^2/W]	$R_{th,sys}$ [K-cm^2/W]
1	37.73	197.9	197.9	0.142	0.120
2	34.12	209.7	209.7	0.119	0.071
3	34.32	215.5	215.5	0.118	0.071
4	41.29	203.8	203.8	0.143	0.109
5	40.24	213.7	213.7	0.134	0.103
6	28.52	237.4	237.4	0.130	0.020
7	35.85	231.7	231.7	0.145	0.063
8	33.13	234.3	234.3	0.139	0.047
9	30.78	246.7	246.7	0.130	0.033

The condenser effectivenesses of three evaporators are demonstrated in Fig. 2. The condenser effectivenesses of Evaporator 2 are between 25.42% and 66.41%. For the given heat dissipation rate of 200-310 W and compressor speed of 4500-5500 rpm, the effectivenesses of Evaporator 1, Evaporator 2, and Evaporator 3 are ranged from 20.88% to 37.88%, from 25.77% to 67.22%, and from 16.66 to 21.58%, respectively. At a given heat dissipation rate of 310 W, the effectiveness of Evaporator 2 are higher than those of Evaporator 1 and Evaporator 3 by 6.99-13.24% and 33.96-42.04%, respectively.

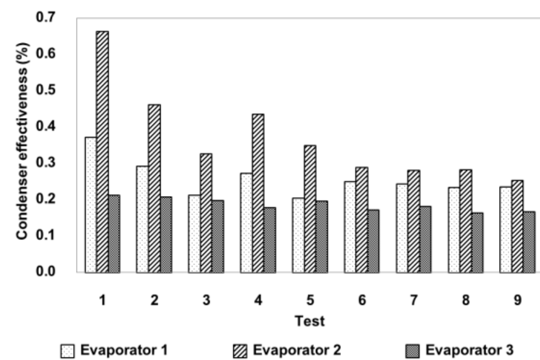

Fig. 2 Condenser effectiveness of three evaporators.

Fig. 3 shows overall system COPs of three evaporators. The resutls shows that for heat dissipation rate between 200 and 310 W, the overall system COP of Evaporator 2 are higher than those of Evaporator 1 and Evaporator 3. For instance, at heat dissipation of 200 W and the compressor speed from 4500 to 5500 rpm, the overall system COPs of Evaporator 2 are higher than that of Evaporator 1 and Evaporator 3 by 2.60-9.80% and 7.38-12.50%, respectively.

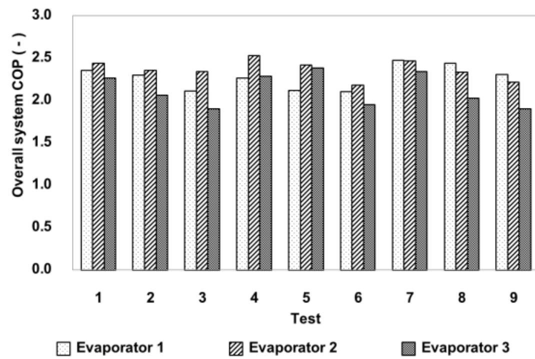

Fig. 3 Overall system Coefficient of Performance (COP) of three evaporators.

Fig. 4 compares the evaporator thermal resistance characteristics of three evaporators. The evaporator thermal resistances of Evaporator 2 are lower than those of Evaporator 1 and Evaporator 3 by 38.70-50.02% and 37.04-50.92%, respectively. For a given compressor speed ranged from 4500-500 rpm, the evaporator thermal resistance increases as the heat dissipation rate increases, since the increase of chip surface temperature is greater than the increase of heat dissipation rate. The evaporator thermal resistances of Evaporator 2 are between 0.3803 and 04107 K-cm^2/W.

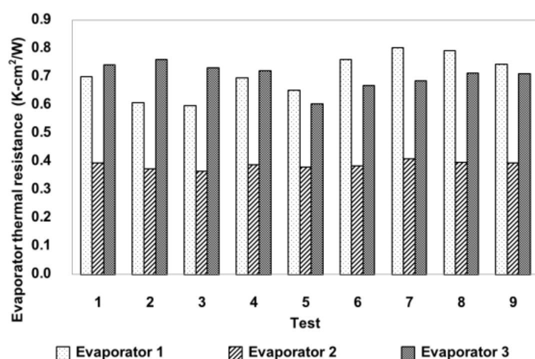

Fig. 4 Evaporator thermal resistance of three evaporators.

The overall system thermal resistances of three evaporators are illustrated in Fig. 5. The overall system thermal resistances of Evaporator 1, Evaporators 2, and Evaporator 3 are ranged from 0.0764 to 0.2805 K-cm^2/W, -0.1071 to -0.2646 K-cm^2/W, and -0.1354 to 0.0133 K-cm^2/W, respectively. It is found that the Evaporator 2 has the lowest overall system thermal resistance and negative values, since the chip surface temperatures are lower than the condenser air inlet temperatures.

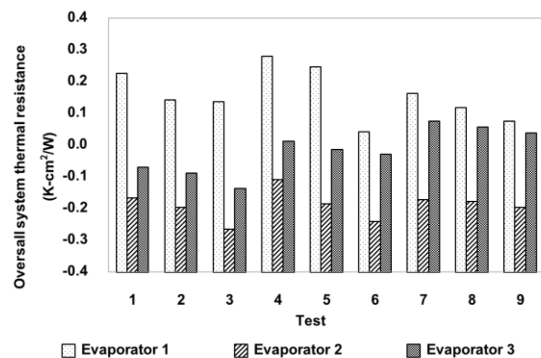

Fig. 5 Overall system thermal resistance of three evaporators.

5. Conclusion

A bread board small-scale vapor compression refrigeration system (SSRS) using R-134a as the refrigerant was designed, built, and tested. The experimental results showed that the refrigeration system using Evaporator 2 can dissipate chip heat fluxes of approximately 49.15-65.25 W/cm^2 and maintain the chip surface temperature between 10.12°C and 19.85°C for a chip size of 2.0 cm^2. Evaporator 2 has a hydraulic diameter of 1.253 mm and aspect ratio (depth/width) of 5.06.

6. Acknowledgements

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