

2008

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Ooi, Kimtiow; Teh, Yongliang; Ng, Florence Pei Fan; and Phay, Tiewtoon, "A Novel Thermal Solution for Electronics Cooling, Part II: Design of a Multi-Evaporator Refrigeration System" (2008). *International Refrigeration and Air Conditioning Conference*. Paper 965.
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A NOVEL THERMAL SOLUTION FOR ELECTRONICS COOLING, PART II: DESIGN OF A MULTI-EVAPORATOR REFRIGERATION SYSTEM

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ABSTRACT

In the electronics cooling industry, it is often desired for production efficiency that a single-compressor-multi-evaporator system be used for the testing of multiple IC units. In this paper, the design of a new multi-evaporator system which features independent control of the cooling capacity at each evaporator using only single-input-single-output control is presented. Although the system utilizes only a single compressor, the cooling capacity at each evaporator can be accurately controlled as individual evaporator lines are decoupled from each other using a common “accumulator”. Furthermore, the compressor only responds to an averaged pressure input in the accumulator only either through conventional on/off control or speed variation. Coupled with the Thermal Control Unit (TCU) presented in Part I of this paper series, it is believed that the new refrigeration cooling system can provide an effective and cost-efficient thermal solution for the electronics cooling industry.

1. INTRODUCTION

Chilled water cooling technology has been commonly used in thermal testing for microprocessor. However, for such systems, it is found that the power densities in packaged microprocessor devices are within the 50 to 100 W/cm² (Tadayon, 2000, Kromann, 1996 and Malinowski et al., 1998). As the power requirement of the microprocessor device is getting higher, the single phase flow technology is reaching its limits in the cooling of microprocessor at lower temperatures. In order to overcome such restrictions, the use of two-phase liquid-vapour flow has been considered.

In Part I of this paper series (Ooi *et al.*, 2008), the design of the thermal control unit (TCU) being employed in the thermal solution for electronics cooling has been presented. In order to have effective heat transfer at the TCU, it is essential to utilize two-phase flow which capitalizes on the high heat adsorption ability of the latent heat of vaporization. Hence, it is proposed that a vapour compression system be used in conjunction with the TCU for achieving the desired high heat transfer capability.

To date, there have been applications in which vapour compression systems are used for electronics cooling, and the application is often conducted on a single device at any one time. Therefore, it may not be as cost effective and efficient to implement in industrial applications such as a test handler system which conducts simultaneous testing on several electronic devices. Therefore, it is the purpose of this paper to introduce a new vapour compression system which uses a single compressor to provide the concurrent testing of multiple devices under test (DUT). In

addition, it is designed to handle multiple DUTs with the ability of handling conditions where each DUT may require dissimilar cooling capacity and yet under a different thermal cycle.

2. DESIGN OF A MULTI-EVAPORATOR REFRIGERATION SYSTEM

2.1. Single TCU System

As shown in Figure 1, the vapour compression circuit is comprised of main components largely found in a conventional refrigeration circuit, namely, 1) a compressor for driving the flow, 2) a condenser for heat rejection to the environment, and 3) a thermal control unit (TCU) which takes the role of an evaporator for heat removal from a DUT. Upstream of the TCU is an automatic expansion valve for the purpose of maintaining the pressure differential required to attain the conditions for heat adsorption at the TCU and heat rejection at the condenser. This is in contrary to a conventional refrigeration system in which a thermostatic expansion valve is used, and the purpose of such a contradiction will be explained later. At the downstream of the TCU is a flow-regulating valve which is regulated by a control system for regulating the amount of refrigerant flow and thus the cooling capacity at the TCU.

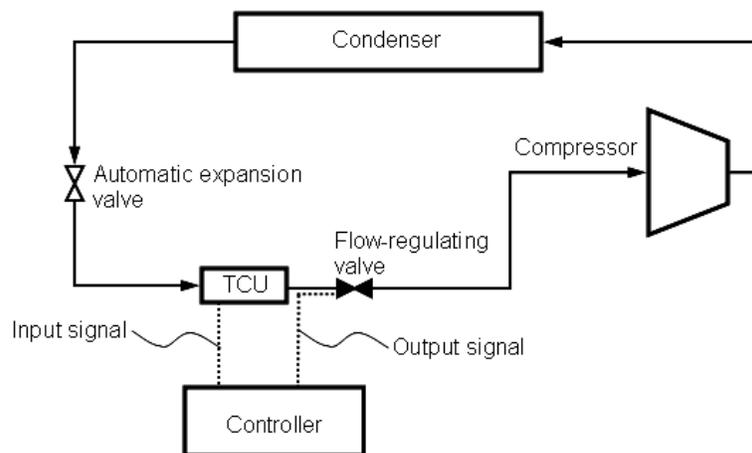


Figure 1: Schematic Diagram of Single TCU System

During operation mode, for example, when the heat generated by the DUT increases, a rise in the DUT temperature is expected. The DUT temperature is sensed by a temperature sensor, such as a thermocouple, which outputs an electrical signal in the form of voltage or current to the control system which controls the flow-regulating valve. The 'incremental' temperature above the set point when detected by the control system causes the flow area at the regulating valve to be increased, and thus resulting in a larger flow rate across the TCU. At this instant, the pressure at the downstream of the automatic expansion valve (upstream of the flow-regulating valve) drops momentarily, and the automatic expansion valve responds automatically to increase its flow area resulting in more flow across the valve and hence recovering the fluid pressure at the TCU. As a consequence, the combined action of the flow regulating valve and the automatic expansion valve results in an increased flow rate of the heat transfer medium and thus the cooling capacity at the TCU, therefore removing the additional heat generated and maintaining the temperature set-point of the device.

On the other hand, in the case of a decrease in heat generation by the DUT, the opposite happens and the flow areas at both valves are reduced, resulting in a lower flow rate and hence reducing the cooling capacity at the TCU, once again maintaining the temperature set-point of the device.

In essence, this new design of a vapour compression system achieves ease of control of the cooling capacity at the evaporator, needing only a single input signal (DUT temperature) and a single output signal (flow regulating valve flow area). Active variation of cooling capacities can be easily attained by simply altering the temperature set-point. Last but not least, the single TCU system described above can be easily expanded into a multi-TCU system with exceedingly simple additions. It is exemplified in the forthcoming section.

2.2. Multi-TCU System

The single TCU system described in the previous section allows a controlled testing process to be conducted on a single device at any one time. However, for productivity reasons, it will be desired that several TCUs be employed in a single main circuit (having only one compressor), with yet the capability of achieving individual control of each TCU. This can be done with simple additions, described as follows.

Expanding from its basic form as described in the single TCU system, Figure 2 shows the multi-TCU system which is further comprised of 1) a receiver, 2) an accumulator and 3) multiple TCU lines each comprising of an automatic expansion valve, a TCU and a flow-regulating valve. Each evaporator line is connected to the receiver upstream and the accumulator downstream, where the latter perform the function of reservoirs to and from which the refrigerant flow through each TCU is drawn from. The cooling capacity at each TCU maintains independent control by the combined action of the flow-regulating valve and the automatic expansion valve as described earlier. In order to ensure sufficient flow of refrigerant through each TCU, the pressure at the accumulator is monitored by the control system. For example, when the heat being absorbed at the TCUs increases, there is a larger amount of refrigerant flow into the accumulator which results in a pressure rise in the accumulator. The increase in the accumulator pressure above its set point would be sensed by a pressure transducer and thus activates the control system which causes the variable speed compressor to be driven faster and resulting in more refrigerant being drawn out of the accumulator. Thus, the prescribed accumulator pressure is restored. Correspondingly, more heat is rejected at the condenser as the refrigerant flow channeling out of the compressor increases. The increased refrigerant flow eventually reaches the receiver replenishing its supply to the TCUs. Predictably, the opposite occurs in the case of an overall decline in heat adsorption at the TCUs.

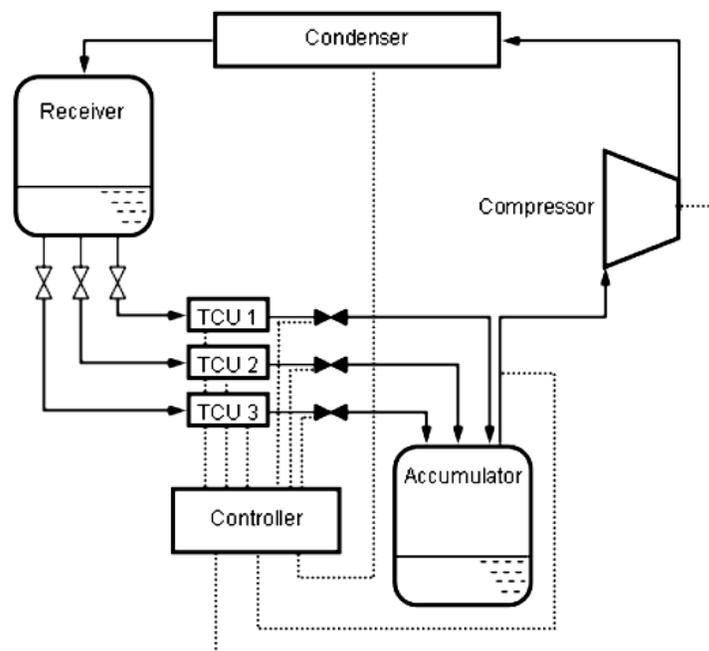


Figure 2: Schematic Diagram of Multi-TCU System

The above exemplifies a simple multi-TCU system capable of achieving independent control of each TCU unit. The use of a pressure set-point at the accumulator as one of the input signal for the control system means that one does not have to actively monitor and control of the main circuit; changes are automatically made to ensure the proper operating conditions being attained at all time. In addition, the control algorithm is easy to implement as the control of the main circuit and the individual evaporator line is totally uncoupled from each other. This feature indicates a high controllability of individual TCUs with good accuracy and short response time, as changes made to the main circuit do not have to be corresponded by actively controlling the individual evaporator lines. Also, this system is in fact particularly suited to accommodate a large number of TCU lines as pressure fluctuations at the accumulator will

be less affected by changes made at an individual TCU. In conclusion, a simple yet reliable and effective multi-TCU system for all kinds of cooling processes has been achieved.

3. System Validation

3.1. Experimental Setup

The single TCU system has been set up for validation of the concept. The refrigerant fluid used is R404A. A heater block (here after refers to as simulator) consisting of cartridge heaters is used to simulate the DUT and it is placed in contact with the TCU. The cartridge heaters are connected to a control system for regulating the heat supplied to the TCU. Lastly, a motorized flow valve is located downstream of the TCU and is connected to the control system. A PID algorithm is used to control the valve opening through the temperature feedback of the thermocouple at the DUT in order to regulate the fluid flow.

Measurement instruments such as pressure transducers and thermocouples are placed before and after each component for data collection in order to understand the fluid medium conditions during the heat transfer process. The data acquisition includes TC1, VP, Q_{in} and T_{set} . TC1 refers to the temperature measurement at the contact surface of the simulator; VP refers to the flow valve opening measured in steps of electric pulses, Q_{in} refers to the heat supplied to the TCU and T_{set} refers to the temperature set point at the simulator contact surface with the TCU.

3.2. Results and Discussions

An experiment is conducted with various heat inputs at the simulator to test the valve response of the system to maintain the temperature of TC1. The heat inputs are tuned down from 600 W to 350 W in steps of 50 W and each test is given a time interval of 15 minutes to reach steady state conditions. Figure 3(a) shows the response of the valve position at the various heat loads supplied. It is observed that the closure of the valve increases when the heat input is reduced, with step transitions at every heat input change of 50W. Local fluctuations of the valve opening at a constant heat load are also observed. These changes are made by the PID control system automatically in attempt to maintain TC1 at the T_{set} of 15 °C. Figure 3(b) shows the variation of TC1 during the course of this experiment, which indicates the effectiveness of the PID control system. TC1 is being maintained at the required temperature with fluctuations mostly within ± 1 °C. It is to be noted that the temperature fluctuations are partly due to the fluctuation at the heat source, in which its supply originates from a time-based on/off control. Nevertheless, a good performance of the new system in maintaining a steady temperature has been shown.

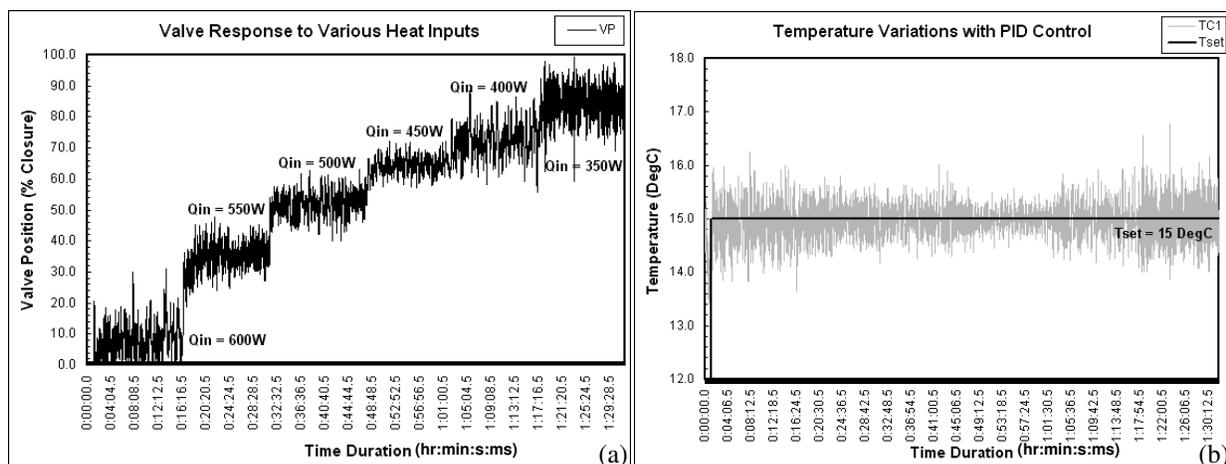


Figure 3: (a) Valve Response to Various Heat Inputs; (b) Temperature Variations with PID Control

In the next experiment conducted, the system is tested for its responses to two types of input changes, namely (1) a change in the Q_{in} at a fixed T_{set} , and (2) change in T_{set} at a fixed Q_{in} . After each change, the system is kept steady for 15 minutes for stabilization. Figure 4(a) shows the changes in the input variables to test the response of the system, which is correspondingly shown in Figure 4b.

In Figure 4(b), it is observed that during the changes in Q_{in} from 600 W to 450 W and vice versa, the valve position changes accordingly in order to maintain the temperature at TC1 at the prescribed T_{set} of 15 °C. Next, by holding the heat supply Q_{in} as constant at 450 W, T_{set} is varied from 15 °C to 35 °C. The temperature offset between TC1 and T_{set} is increased suddenly which causes the valve to close as less cooling is required. It is noted that the valve is fully closed at one point in the initial stage of the response highlighted in circle 1 to attain the new T_{set} of 35 °C in the shortest possible duration. A similar valve response is also observed as indicated in circle 2 when T_{set} is reverted back to 15 °C, in which the valve temporarily attains a full opening. In both cases TC1 can be observed to reach T_{set} within a short duration of time.

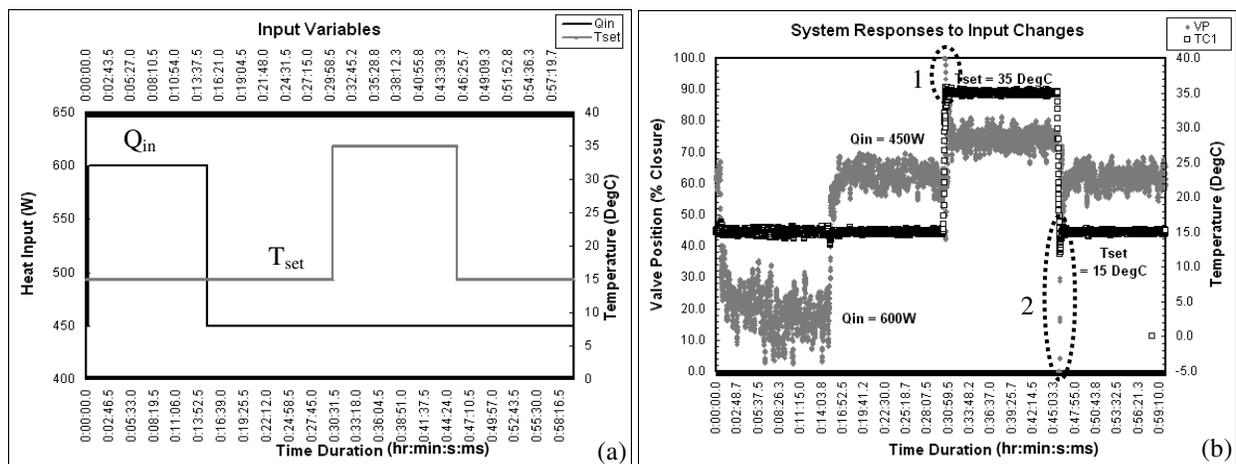


Figure 4: (a) Input Variables to System; (b) System Response to Input Changes

4. CONCLUSIONS

In this paper, a new multi-evaporator refrigeration system which features independent control of the cooling capacity at each evaporator using only single-input-single-output control is presented. The combined action of the automatic expansion valve and flow regulating valve allows the cooling capacity at the evaporator to be controlled for testing of electronics devices under various heat loads and thermal cycles. At present, the verifications have only been carried out on a single TCU refrigeration circuit which has succeeded in demonstrating the functionality of the new system. As for the multi-TCU system validation, it is still in the progress of development.

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ACKNOWLEDGEMENT

This research is supported by AEM Singapore Pte Ltd. The authors would like to thank AEM Singapore Pte Ltd for providing the necessary resources to ensure the smooth operation of project.

