Experimental Study on Effects of Inlet Water Temperature on the Ramp Rate of a Thermal Chamber having a Cascading Refrigeration System with A 3-Loop PID Controller

N. Venu Mohan[1] Mukesh Kumar[2] S. Giridhar Rao[3]
[1]Technical Officer 'A' [2]Scientist 'E' [3]Scientist 'F'
[1,2,3]Department of Advanced Systems Laboratory
[1,2,3]Dr.APJ Abdul Kalam Missile Complex, DRDO, Hyderabad, India

Abstract— A thermal chamber is an enclosure which is used to test the effects of specified environmental conditions on electrical and electronic components of defense and aerospace applications. These environmental chambers contain a heating system and a refrigeration system to simulate hot and cold environmental conditions respectively. During the refrigeration cycle, a lot of heat will be generated which has to be removed from the chamber for achieving a higher ramp rate. The heat removal process is effective when the inlet water temperature of the chamber is minimum. An experimental study has been conducted to analyze the variations in the ramp rate of a thermal chamber with respect to the changes in the inlet water temperature. This inlet water basically goes to the heat exchanger of the refrigeration system. The experimental results show that inlet water temperature has a direct impact on the achieved ramp rate of the thermal chamber when the set ramp rates are between 7ºC/min to 10ºC/min, a very less impact when the set ramp rates are between 2ºC/min to 6ºC/min and almost negligible impact when the set ramp rate is 1ºC/min. In this paper, optimum inlet water temperature for various ramp rates is also identified.

Key words: Ramp Rate, Environmental Chamber, Inlet Water Temperature, PID Controller, Cascading Refrigeration System, Heat Exchangers

I. Introduction

A thermal chamber is an enclosure, which is used to carry out different types of environmental tests on electrical and electronic components of defense and aerospace applications to find out the latent defects, which occur during the manufacturing, assembling and workmanship stages. One of the most important environmental test is temperature cycling in which, unit under test (UUT) is exposed to two extreme temperatures in a cyclic manner, and the ramp rate generally followed is between 5ºC/min to 20ºC/min. The applied thermal stress will convert latent defects into hard failures.

II. Significance of Ramp Rate in Thermal Screening Process

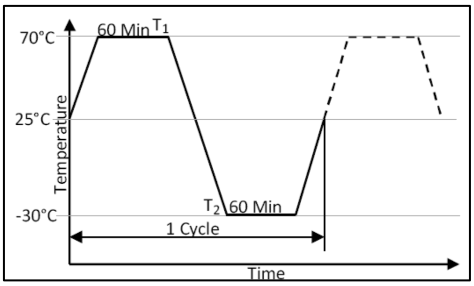

Fig. 1: Temperature Cycling Profile

Ramp rate can be defined as rate of change of temperature per minute.

$$\text{Ramp Rate} = \frac{T_1 - T_2}{\Delta t}$$

T_1 = Maximum Temperature to which the screened item is exposed
T_2 = Minimum Temperature to which the screened items is exposed
Δt = Transition time from T_1 to T_2 in minutes

The ramp rate of the thermal chamber is more important in inducing the thermal stress on the screened items. As the ramp rate increases, its effectiveness in precipitation of the failures i.e. screen strength[8] also increases.

III. Research Problem

During the temperature cycling from +70ºC to -30ºC, a water cooled thermal chamber, which is rated for 10ºC/min ramp rate, is able to achieve only 6ºC/min ramp rate, when the ambient temperature increases above 30ºC.

Fig. 2: Thermal Chamber

Internal Dimensions	1000mm x1000mm x 1000mm
Temperature Range	-73 º C to +177 º C
Ramp Rate(max)	10 º C/min
Refrigeration System	Cascade type
Condenser	Shell and tube type
Refrigerants	R-23 (low Stage) R-404A (high stage)
Cooling method	Water Cooled
Cooling Tower	Cross flow Type
Controller	Microprocessor based 3 loop PID controller

Table 1: Thermal Chamber Technical Specifications

A. *Refrigeration System of the Chamber*

Thermal chamber used for the experimental studies is having a cascading refrigeration system [14] with R-23 as a low stage refrigerant and R-404A as a high stage refrigerant with semi hermitic compressors. Maximum achievable ramp rate of the chamber is 10°C/min between the temperatures from +85°C to -40°C. Heat exchanger (i.e. Condenser) is shell and tube type which is cooled by a 30TR water cooling tower which is cross flow type.

B. Temperature Controlling Mechanism

Temperature inside the chamber is controlled through a 3-loop PID Controller.

IV. PROBLEM ANALYSIS

The low ramp rate of thermal chamber may occur due to the leakage of refrigerants, malfunctioning of the compressors, condensers, evaporators or thermal expansion valves. It was ensured that there is no leakage in the refrigeration system by using bubble method [18]. After thorough investigation it was found that, low ramp rate of the chamber is due to decrease in the heat transfer efficiency of the heat exchanger which is shell and tube type.

Shell and tube type heat exchanger consists of large number of tubes located in a steel shell, with water flowing inside and refrigerant vapor flowing outside the tubes. The vapor condenses on the exterior surface of the tubes due to heat exchange between the water and the refrigerant vapor.

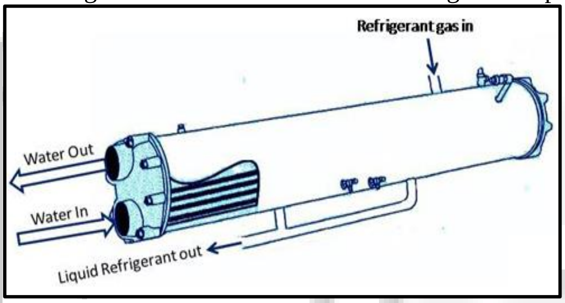

Fig. 3: Shell and tube heat exchanger

In a heat exchanger, the heat transfer rate (Q) can be defined as follows.

$$Q = U*A*\Delta T_{LM} \quad (2)$$

Q = Heat Transfer rate (Watts = Joules/Sec)
U = Overall heat transfer coefficient ($W/m^2 \, ^oC$)
A = Heat transfer surface area(m^2)
ΔT_{LM} = Logarithmic mean temperature difference

As per the above formula, to increase the efficiency of a water cooled heat exchanger, either we have to increase the heat transfer surface area(A) or to increase the temperature difference(ΔT_{LM}) between refrigerant gas vapor and the water.

We cannot increase the surface area of the heat exchanger, as it is fixed by the manufacturer at the design stage of the chamber itself. So the other possibility is to increase the temperature difference between the refrigerant gas vapor and the water which is entering into the heat exchanger. This can be achieved either by decreasing the inlet water temperature of heat exchanger or increasing the volume of water flowing through the heat exchanger.

By applying the above rule, inlet water temperature of the thermal chamber is decreased by adding 50Kgs of ice to the water storage tank of the cooling tower and then ramp rate of the chamber is tested. After addition of ice, the achieved ramp rate of the thermal chamber is increased from 6ºC/min to 8ºC/min, when the set ramp rate is 10ºC/min. Hence a detailed research work is carried out to identify the behavior patterns of the ramp rate of the thermal chamber with respect to the variations in the inlet water temperatures.

V. OBJECTIVES OF THE EXPERIMENT

First, to identify the effects of inlet water temperature on the ramp rates achieved by the thermal chamber. Second, to identify the optimum inlet water temperature for achieving maximum ramp rate.

VI. EXPERIMENTAL SETUP AND PROCEDURE

To identify the effect of inlet water temperature on the achieved ramp rate of the chamber, the same thermal chamber was used. Instead of a cooling tower, a 30 ton air cooled chiller is connected to the thermal chamber, which is having R-137 as a refrigerant. Chiller is a refrigerating unit which cools water through vapor compression refrigeration method.

Fig. 4: Water Chiller

Cooling Capacity	30 TR
Temperature range	10º C to 25 º C
Liquid Type &Qty	Water – 1000 Liters
Condenser Type	Air Cooled
Refrigerant	R-137 C
Pump	400 LPM, 5 Bar

Table 2: Water Chiller Technical Specifications

The Chiller which is connected to thermal chamber is having a capacity to cool the water between the temperatures from +25ºC to +10ºC. The chiller is filled with 1000 liters of de-mineralized water. Initially, water tank temperature of the chiller is set to 25ºC, and chiller is kept in running condition for about 30 minutes to ensure that, temperature inside the storage tank which is going as inlet water to the heat exchanger of the thermal chamber will also attains the temperature of 25ºC. During the entire experiment, PID values of the both chamber and chiller are kept unchanged.

The set thermal profile is as follows.

- Increase the temperature from ambient to +70ºC
- Dwell for one hour at +70ºC
- Decrease the temperature from +70ºC to -30ºC
- Dwell for one hour at -30ºC

During the experiment, set temperatures and achieved temperatures inside the chamber are recorded through itools software. While calculating the ramp rate, JESD22-A104D method is followed which states that, ramp rate should be measured for the linear portion of the profile curve, which should be 10% and 90% of the test condition temperature range. Hence ramp rates are calculated between +60ºC to -20ºC during the temperature cycling from +70ºC to -30ºC.

In this experiment, the test is repeated by decreasing the inlet water temperature from 25ºC to 10ºC in the steps of 2.5 ºC and ramp rates from 10ºC/min to 1ºC/min in the step of 1ºC/min . Data is recorded in the table.

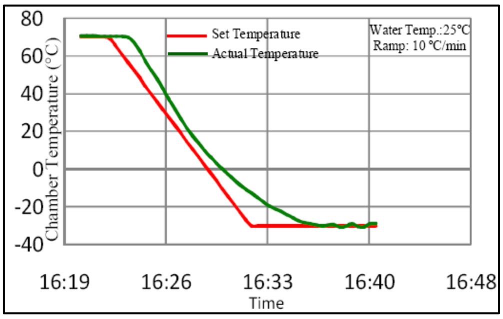

Fig. 5 (a): Test

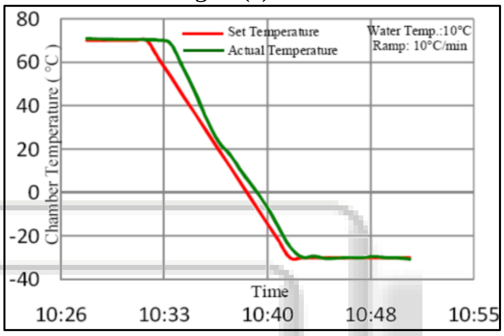

Fig. 5(b): Test

Set Ramp (ºC/min)	Achieved Ramp Rates (Down Ramp) (from +70ºC to -30ºC)						
Water Temperature	25.0	22.5	20.0	17.5	15.0	12.5	10.0
10	7.4	7.52	7.72	8.06	8.26	8.78	9.99
9	7.1	7.25	7.56	7.76	8	8.56	8.96
8	6.86	7.28	7.42	7.55	7.75	7.85	7.99
7	5.97	6.22	6.49	6.62	6.86	6.89	6.99
6	5.91	5.95	6.00	6.00	6.00	6.00	6.00
5	4.93	4.95	5.00	5.00	5.00	5.00	5.00
4	3.92	3.97	4.00	4.00	4.00	4.00	4.00
3	2.97	2.99	3.00	3.00	3.00	3.00	3.00
2	1.97	1.99	2.00	2.00	2.00	2.00	2.00
1	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Table 3: Achieved ramp rates at various Inlet Water Temperatures

Fig 5 (a) & (b) Shows the variation in the ramp rate of the chamber due to variation in inlet water temperature. When the inlet water temperature is 25ºC, achieved ramp rate is 7.4ºC/min (Fig. 5 (a)) and the ramp rate increased to 9.99ºC/min (Fig.5(b)), when inlet water temperature is decreased from 25ºC to 10ºC.

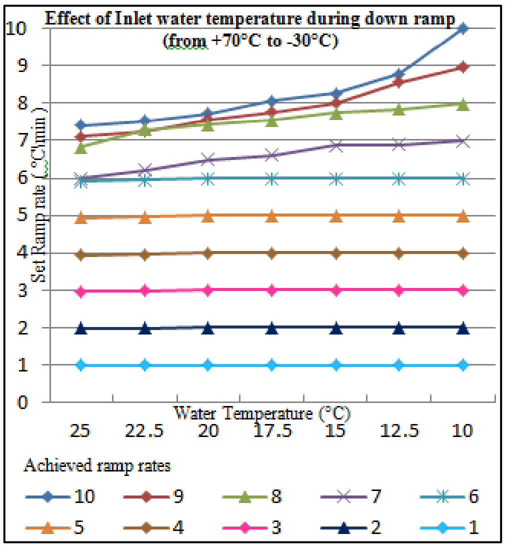

Fig. 6: Effect of inlet water temperature on ramp rate

Table (3) & Fig.6 Shows the complete list of all ramp rates achieved under various inlet water temperature conditions during down ramp.

VII. RESULTS AND DISCUSSION

A. Effect of Inlet Water Temperature between the Set Ramp Rates from 7ºc/Min to 10ºc/Min

From the experiment it is found that, inlet water temperature has a direct impact on the achieved ramp of the thermal chamber between the set ramp rates from 7ºC/min to 10ºC/min. When the inlet water temperature is decreased by 15ºC (from 25ºC to 10ºC), percentage of increase in the achieved ramp rate is maximum during the set ramp rate of 10ºC/min. This occurs due to increase in the heat transfer efficiency of the heat exchanger by increasing the temperature difference between the refrigerant gas vapor and the water. But the percentage of increase in the achieved ramp rate is gradually decreases with the decrease in the set ramp rates as follows.

Set Ramp Rate (ºC/min)	Achieved Ramp Rates (ºC/min)		% of increase in ramp rate
Water Temp.	25 ºC	10 ºC	
10	7.4	9.99	35.00
9	7.1	8.96	26.19
8	6.84	7.99	16.81
7	5.99	6.99	16.69

Table 4: Percentage of increase in ramp rate due to decrease in inlet water temperature

B. Effect of Inlet Water Temperature between the Set Ramp Rates from 6ºc/Min to 2 ºc/Min

During the set ramp rates from 6ºC/min to 2ºC/min, the thermal chamber is able to achieve the maximum set ramp rate, when the inlet water temperature is decreased from 25ºC to 20ºC. Hence further decrease in the inlet water temperature does not have any impact on the achieved ramp rate of the thermal chamber due to the controlling mechanism of the 3 loop PID Controller.

C. Effect of inlet water temperature at the set ramp rate of 1ºC/min

Inlet water temperature does not have any impact on the achieved ramp rate of thermal chamber when the set ramp rate is 1ºC/min ,as the chamber is able to achieve the maximum set ramp rate when the inlet water temperature is at 25ºC.

D. Optimum Inlet Water Temperatures for Various Ramp Rates

By analyzing all the ramp rates of the thermal chamber with respect to various inlet water temperatures, the optimum inlet water temperature is 10ºC when the set ramp rates are 10ºC/min to 7ºC/min, 20ºC for 6ºC/min to 2ºC/min and 25ºC for 1ºC/min.

VIII. CONCLUSION

In this research paper, low ramp rate of a thermal chamber is analyzed and an experimental study has been conducted to identify the effects of inlet water temperature on the ramp rate of a thermal chamber. Ramp rate of the thermal chamber is increased from 6ºC/min to 9.99ºC/min, when the inlet water temperature is decreased from 25ºC to 10ºC. From the experiment it is found that inlet water temperatures have a direct impact on the achieved ramp of the chamber. At the end, optimum inlet water temperatures for various ramp rates are also identified for achieving the maximum ramp rate.

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