# Temperature Characteristics of Cascade Refrigeration System by Pressure Adjustment

**Han-Shik Chung, Hyo-Min Jeong***
*School of Mechanical and Aerospace Engineering, the Institute of Marine Industry, Gyeongsang National University, 445 Inpyeong-dong, Gyeongsang-namdo 650-160, Korea*
**Yeong-Geun Kim, Lubi Rahadiyan**
*Graduate School, Department of Mechanical and Precision Engineering, Gyeongsang National University, 445 Inpyeong-dong, Gyeongsang-namdo 650-160, Korea*

Super low temperature has many applications nowadays, from the chemical processing, automotives manufacturing, plastic recycling, etc. Considering of its wide application in the present and the future, study of the super-low temperature refrigeration system should be actively carried out. Super low state temperature can be achieved by using multi-stage refrigeration system. This paper present the development and testing of cascade refrigerator system for achieving super-low temperature. On this experiment, two different types of HCFCs refrigerants are utilized, R-22 and R-23 were applied for the high stage and the low-pressure stage respectively. The lowest temperature in the low-pressure evaporator that can be achieved by this cascade refrigeration system is down to −85℃. This experiment is aimed to study the effect of inlet pressure of the low-pressure stage evaporator and low-pressure stage compressors inlet pressure characteristics to the overall temperature characteristics of cascade refrigeration system.

**Key Words :** Cascade Refrigerator System, High Pressure Stage, Low Pressure Stage, Variable Expansion Valve

## 1. Introduction

CFCs developed in the 1930's have been most widely used in the field of refrigeration since they almost perfectly satisfied the requirements for good thermodynamic properties, chemical stability, non-flammability, non-toxicity etc (Kim et al., 1998). To get more high performance of refrigerator, many of researches had been carried out for heat transfer in a tube like cascade heat exchanger by Gungor et al.(1986), Jung et al. (1989) and Kandlikar (1990), but these researches had a focus on the simple pipe or tube for two phase flow and boiling phenomena. All of these reports were considered about the heat transfer for parts that have a single stage refrigeration system. For instance, Kuo et al.(1996) and Adriana et al.(2004) reported about the evaporating heat transfer for horizontal tube, and Shah (1982) suggested a correlation equations for saturated boiling heat transfer.

The conventional refrigerator can only reach low temperature down to −40℃. If the lower temperature is required, multi-stage refrigeration system must be utilized. Cascade or two-stage refrigerator is one of type of multi-stage refrigeration system to reach super low temperature condition. A cascade-condensing unit consists of two

* Corresponding Author,
**E-mail** : hmjeong@gsnu.ac.kr
**TEL** : +82-55-640-3184; **FAX** : +82-55-640-3188
School of Mechanical and Aerospace Engineering, the Institute of Marine Industry, Gyeongsang National University, 445 Inpyeong-dong, Gyeongsang-namdo 650-160, Korea. (Manuscript **Received** June 7, 2005; **Revised** November 15, 2005)

refrigeration systems ; both of them are separate unit. The heat exchanges between two refrigerants is carried out by the cascade heat exchanger. It consists of a cascade evaporator in the higher stage, and cascade condenser in the lower stage.

The high-pressure stage refrigerator, which is called or high-temperature stage, is utilized for cooling the condenser of the low-pressure stage, which also called low-temperature stage. Thus, the low-pressure stage can reach the super-low temperature.

This refrigeration system consists of two cycles :

(1) High-pressure cycle : compressor → condenser → expansion valve → cascade evaporator

(2) Low-pressure cycle : compressor → cascade condenser → expansion valve → super-low temperature cooling unit (low-pressure evaporator)

Generally cascade high-pressure evaporator and cascade low-pressure condenser are installed coaxially in the cascade heat exchanger. The high-pressure evaporator pipe is placed inside the low-pressure condenser.

On the other hands, as the performance of refrigerator is influenced by the evaporator, recently, almost of studies have a concerning about kinds of refrigerants to get a environmental friendly refrigerants (Havelsky, 2000). These papers showed only that the reports or information of total refrigeration cycle system are not enough.

The one stage refrigeration system is most usual and had been utilized for general industrial fields, but when they need a more low temperature, the general one stage refrigeration system can not be used and they need a two stage refrigeration cycle system. Giovanni et al.(2005) and Agnew et al. (2004) reported about the cascade heat exchanger for need of previous problems. A. Kilicarslan (2004) found that at same refrigeration load interval cascade performance shows higher COP than single stage system.

The high-pressure evaporator can obtain temperature in the range of −20℃ to −30℃ in the expansion valve outlet. At this temperature, low-pressure refrigerant is condensed in the low-pressure condenser (located in the cascade heat exchanger). Super-low temperature area in this system is located from low-pressure expansion valve outlet until low-pressure compressor inlet.

The goal of this experiment is to study the effect of the low-pressure and the high-pressure inlet pressure to the temperature characteristics of cascade refrigeration system by adjusting either of low-pressure and the high-pressure inlet pressure. This experiment use R-22 in the high-pressure stage and R-23 in the low-pressure stage.

## 2. Test Setup

Figure 1 shows measurement points in which the thermocouples are placed to measure the temperature of the system. There are 20 thermocouples installed on the system. Ten thermocouples are installed on the high-pressure stage, and the others are installed on the low-pressure stage.

There are two experimental methods in this

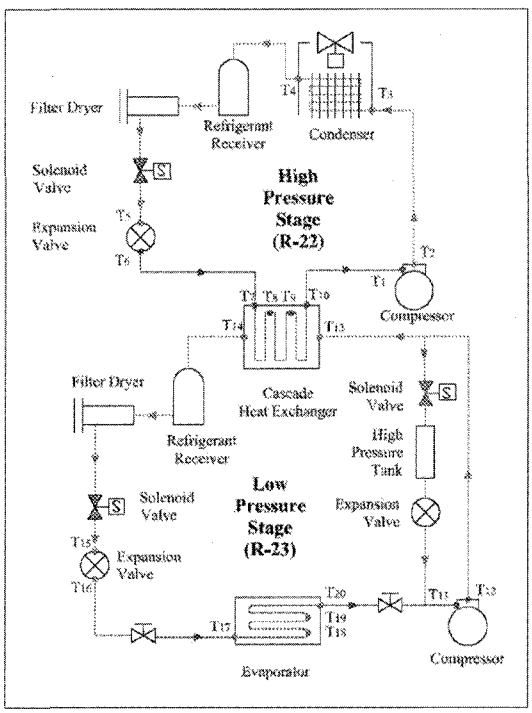


**Fig. 1** Temperature measurement point of cascade refrigeration system

study. The first experiment tries to discover the effect of outlet pressure of the low-pressure stage compressor to performance of the cascade refrigeration system. There are three different pressures at the low-pressure stage compressor outlet for this experiment, first experiments at 5 bars, second at 10 bars and the last experiment at 15 bars. This pressure was achieved by adjusting the mass of R-23 refrigerant in the low-pressure refrigerator system. In the beginning, the refrigerant was discharged, so that the pressure of the compressor outlet is 0.0 bars, then the refrigerant was filled gradually by 5 bars, 10 bars and 15 bars.

On the second experiment, expansion valve of the low-pressure stage was replaced by adjustable Expansion valve. This experiment performed at two conditions. On the first condition, the low-pressure stage compressor inlet was situated below atmospheric pressure. On the second condition, the low-pressure stage compressor inlet was situated over atmospheric pressure.

To measure temperature of the system, T type thermocouples are used since this thermocouple is relatively more stable for low temperature application (−200℃ to −300℃) and more suitable for oxidation atmosphere environment.

The temperature distribution at the 20 thermocouples was recorded using data logger every 10 seconds. Fig. 2, shows the experimental device of cascade refrigeration system.

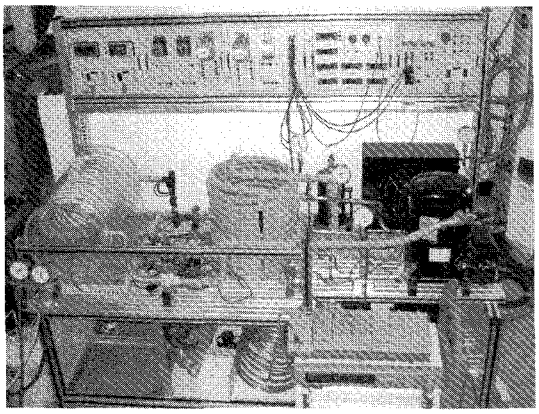

**Fig. 2** Experiment device of cascade refrigeration system

## 3. Result and Discussion

### 3.1 Effect of the outlet pressure of low pressure stages compressor

#### 3.1.1 Compressor outlet pressure : 5 bars

Figure 3 illustrates the general condition of the high stage cascade refrigerator during experiment. High-pressure compressor was turned on 2 minutes after experiment was started. No significant alteration occurs during this time. Low-pressure stage was initiated 5 minutes after. When the high stage compressor was started, temperature of compressor inlet was dropped to −30℃, while cascade evaporator dropped to −37℃. A little shock was occurring because of low-pressure stage starting, but it returned stable at last. No fluctuation observed after 12 minutes.

Compressor outlet, condenser inlet float to 30℃, but it returned decrease. After a low-pressure stage was turned on, Compressor outlet, condenser inlet increased smoothly. After 10 minutes, T2 and T3 had reached its stable condition, and remained constant.

High-pressure stages condenser outlet and temperature of the high-pressure stages expansion valve inlet underwent small elevation after starting time but it remained steady although the low-pressure stage compressor was started. These temperatures only experienced little alteration by the low-pressure stage and it return normal few

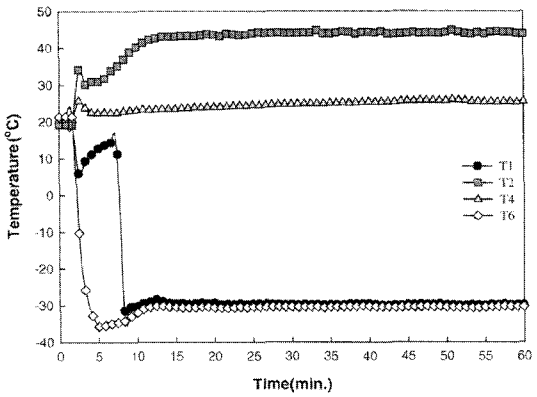


**Fig. 3** Temperature distribution of high pressure stage at compressor outlet pressure : 5 Bars

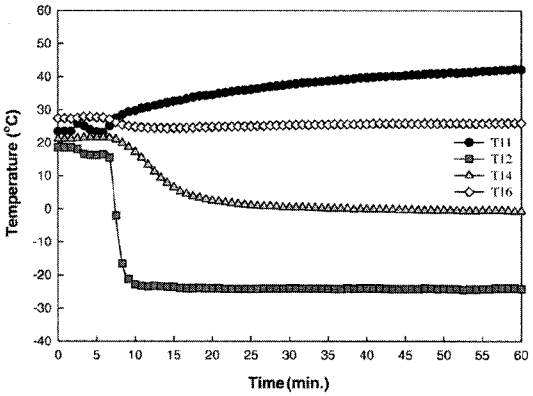


**Fig. 4** Temperature distribution of low pressure stage at compressor outlet pressure : 5 Bars

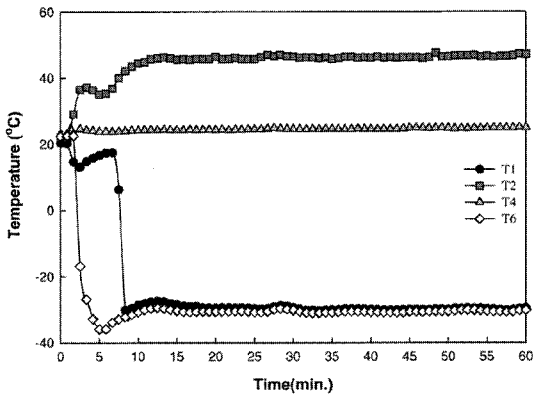


**Fig. 5** Temperature distribution of high pressure stage at outlet pressure of low-pressure compressor : 10 bars

minutes after. It indicates that the low-pressure stage does not affect the expansion valve inlet.

Figure 4 illustrate condition of the low-pressure stage refrigerator. Initial temperature of the low stage was 20℃. After the low stage compressor turned on, temperature of the compressor inlet as well as in the condenser inlet were remaining stable. Until the end of the experiment, it only increases about 5℃. However, in case of condenser inlet, it decreases before the low stage was start because of cooling effect of the high-pressure evaporator.

Temperature in compressor outlet was continually ascending until the end of the experiment. Extraordinary behavior occurred on the temperature of the condenser outlet pressure, since the temperature is lowest among the other. It decreased as son as the compressors was started, and remained stable until the experiment was ended. The temperature at the expansion valve outlet and outlet decreased gently during 10 minutes after low-pressure stage was start, and tend to stable until the end of experiment. The temperature in low-pressure evaporator decrease only about 10℃ during experiment, it seems that the low pressure stage compressor does not work properly on this pressure since the lowest temperature achieved by the low-pressure stage only about 8℃, it relatively far from the normal condition.

### 3.1.2 Compressor Outlet Pressure : 10 bars

Figure 5 illustrate the general condition of the high-pressure stage cascade refrigerator during experiment. High-pressure compressor was turned on 5 minutes after experiment was started. No significant alteration occurred during this time. Low-pressure stage was initiated 5 minutes after.

Temperature of the Compressor outlet, condenser inlet float to 45℃, but it suddenly dropped until the low-pressure stage was started and after that, it continuously increased.

High-pressure stages condenser outlet and temperature of the high stages expansion valve inlet underwent small elevation after starting time but it became steady although the low-pressure stage compressor was started. Both temperatures only underwent little alteration by the low-pressure stage and it return normal few minutes after, it indicates that the low-pressure stage does not give much affect the expansion valve inlet.

When the High stage compressor is started, Temperature of expansion valve outlet and upper and middle part of the evaporator suddenly drop to −40℃. After the low-pressure stage was started, temperature of the upper and middle part of the evaporator was floated to −5℃, and return to −30℃. Meanwhile temperature of expansion valve outlet receives little shock. However, it return steady at −30℃ until the experiment was ended. Nevertheless, the temperature of T6, T7, and T8 underwent small fluctuation after the low-pressure stage was initiated.

Temperature of compressor inlet, lower part of condenser, and condenser outlet dropped to 5℃, then it increase until the low stage was started. T1, T9, and T10 dropped because of low-pressure stage initiation. Temperature of compressor inlet became steady after 25 minutes. Some fluctuation occurs to T9, and T10 but it became smaller as the experiment progressing.

After the low-pressure compressor turned on, the inlet temperature of the low-pressure stage compressor was not yet stable in this experiment, it fluctuated as soon as low-pressure stage was initiated.

Temperature of the compressor outlet as well as the condenser inlet and outlet pressure was constantly increasing. At the beginning, it floated to 65℃, from 5 minutes of initiation of low-pressure stage until the end of the experiment, it increased about 5℃. These temperatures reach 80℃ at the end of experiment. Note that the condenser inlet decreased before the low-pressure stage was start because of cooling effect of the high-pressure evaporator.

Evaporator inlet dropped to −7℃ when low-pressure stage was started, and it decreased gradually and it tended to stable on the 25℃ after 20 minutes, nevertheless very small fluctuation can still be observed.

The temperature of the expansion valve and all temperature in the evaporator were dropped to −70℃ and it gradually decreased to −80℃ in the next 15 minutes. All the temperatures remained stable from 25 minute until the end of experiment.

Figure 6 illustrates condition of the low-pressure stage refrigerator. The Initial temperature was 20℃.

### 3.1.3 Compressor outlet pressure : 15 bars

Figures 6 and 7 show the temperature distributions in case of high and low pressure stage with 15 bars. High-pressure compressor was turned on 5 minutes after experiment was started. No significant alteration occurs during this time. Low-pressure stage was initiated after 5 minutes.

When the high-pressure stage compressor was started, compressor inlet temperature was dropped to −30℃, while cascade evaporator's dropped to −37℃. A little shock was occurring because of low stage starting, but it returned stable. Only small fluctuation observed.

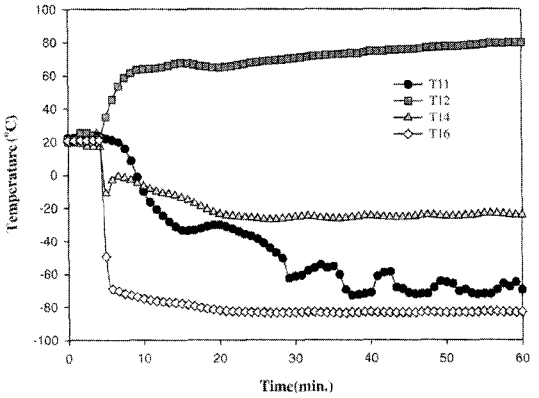


**Fig. 6** Temperature distribution of low-pressure stage at outlet pressure of low-pressure compressor : 10 Bars

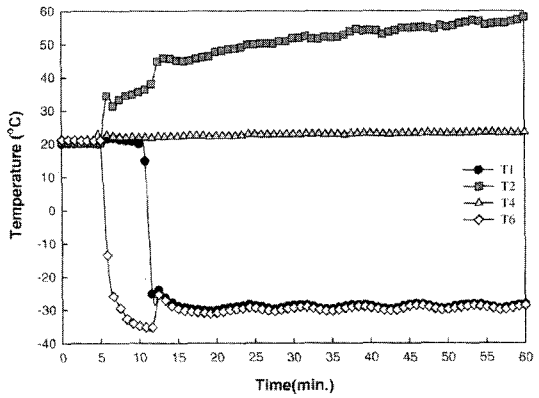


**Fig. 7** Temperature Distribution of High Pressure Stage at outlet pressure of low-pressure compressor : 15 Bars

Compressor outlet, condenser inlet floated to 30℃ and 40℃ respectively, and it continuously increased. The starting of lower stage only gave small effect to these temperatures.

High-pressure stages condenser outlet and temperature of the high stages expansion valve inlet undergo small elevation after starting time but it become steady although the low-pressure stage compressor was started. It indicates that the lower stage does not affect the expansion valve inlet.

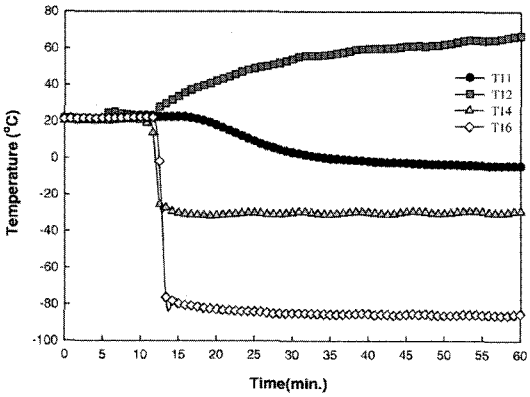


**Fig. 8** Temperature distribution of low pressure stage at outlet pressure of low-pressure compressor : 15 Bars

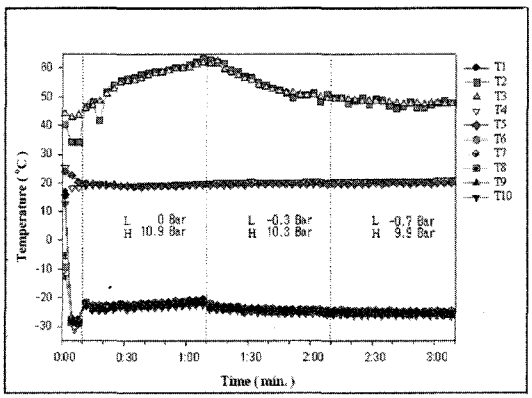


**Fig. 9** Temperature distributions of high-pressure stage, at inlet pressure of low-pressure compressor : 0.0 to -0.7 bars

Initial temperature of the low stage was 20℃. After the lower compressor turned on, the inlet temperature of the low-pressure stage compressor was decreasing smoothly, and it remained constant on 50 minutes.

Temperature of the compressor outlet as well as the condenser inlet was constantly increasing until the experiment ended. Temperatures of compressor outlet reach 70℃ and condenser inlet 50℃ on the 60 minutes. Note that the condenser inlet decreased before low-pressure stage was started because of cooling effect of the high-pressure evaporator.

Evaporator inlet and condenser outlet pressure, drop to −25℃ and remain stable on that temperature. Temperature of the expansion valve outlet and evaporator ware dropped down to −80℃ and remain constant until 60 minutes.

Temperature of lower part of evaporator and evaporator outlet were decreasing gradually until the end of experiment.

### 3.2 Effect of the inlet pressure of low-pressure stage compressor

#### 3.2.1 High pressure stage experiment result

Figures 9 and 10 illustrate experiment result at the first experiments of vacuum pressure condition. For the first hour (00 : 10 to 01 : 10), inlet pressure of the low-pressure compressor was 0 bars. In the high-pressure stage, temperature of compressor outlet and condenser inlet was floated

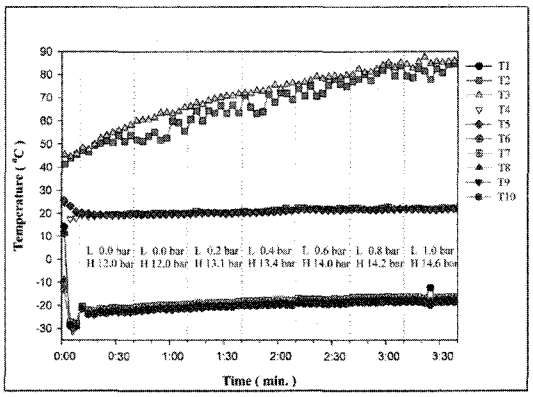


**Fig. 10** Temperature distributions of high-pressure stage, at inlet pressure of low-pressure compressor : 0.0 to 1.0 bar

to 40℃ and 50℃ respectively. In spite of small fluctuation in the beginning, temperature of compressor outlet as well as condenser inlet was gradually increase until the inlet pressure of low-pressure stage compressor was descended to −0.3 bars. From the second hours (1 : 10) when compressor inlet pressure was −0.3 bars, until third hours when pressure was decreased to −0.7 bars, these temperatures gradually decreased.

In the meantime, temperature of condenser outlet and evaporator inlet tended to steady at constant temperature even though the low-pressure compressor inlet pressure was adjusted to −0.3 bars and −0.7 bars.

Temperature of the expansion valve outlet as well as in the high-pressure evaporator and compressor inlet underwent small decrement. However, in the first hours it tended to increase.

In the experiment of over-atmospheric pressure condition (Fig. 10), after low-pressure stage was started, all the temperature tend to increase with different slope as consequences of the inlet pressure increment in the low-pressure compressor. Temperature of compressor outlet and condenser inlet inclined steeper than the other temperature in the high-pressure stage. This means that the compressor work will be increased as the pressure of the compressor inlet increase. Meanwhile, temperature of expansion valve outlet, evaporator inlet, inside, outlet and compressor inlet pressure were increasing slowly.

The lowest temperature attained by the high-pressure stage system is about −27℃, it occurs when the pressure of compressor inlet at −0.7 Bars.

### 3.2.2 Low pressure experiment result

The first experiment of low-pressure stage in the vacuum condition has similar result with the high-pressure stage. All the temperature has a tendency to decrease as the low-pressure stage compressor inlet was decreasing.

When the low-pressure stage inlet compressor is 0.0 bars, temperature of cascade condensers inlet and outlet reached 100℃ and 90℃ respectively. After the pressure was dropped off to −0.3 bars on the next hour, temperature of cascade condensers inlet and outlet dropped to 80℃ and 60℃ respectively. On the following time hours, it tend to constant yet little fluctuation can be observed In the end of experiment, when the pressure was −0.7 bars, temperatures of the compressor outlet pressure was −85℃.

Figure 11 shows that all temperatures tend to decrease when the pressure of compressor inlet pressure was decreased.

On the next experiment, when the compressor inlet pressure was operated more than atmospheric pressure, the temperatures distribution of low-pressure stage is increasing gradually as the inlet pressure was increased.

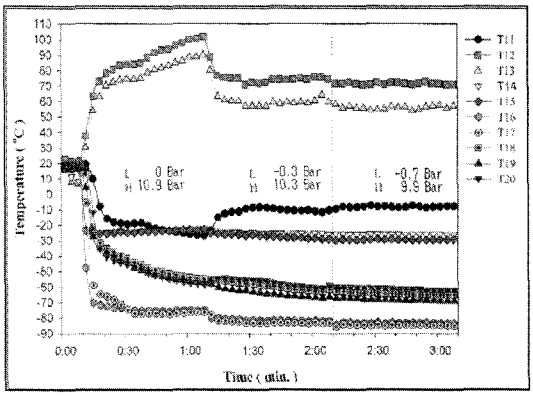


**Fig. 11** Temperature distributions of low pressure stage, at inlet pressure of low-pressure compressor : 0.0 to -0.7 bars

Temperature of low-pressure condenser inlet has relatively in unsteady circumstance; this temperature fluctuates during the experiment. It increases rapidly after starting time from 5℃ to 22℃ than it continue to increase to 103℃ and then tends to unstable in the range of 99℃ to 113℃.

Temperature of at condenser outlet and expansion valve inlet was dropped to −25℃ when the low-pressure stage was started. It continued to decreasing until the end of experiment. Expansion valve outlet, evaporator upper part, at evaporator middle, evaporator lower part at the condenser outlet have similar response, it dropped to about −75℃ in the initiation time. Meanwhile, the temperatures of T16-T20 were increasing gently.

The highest temperature reached by compressor outlet was more than 120℃, it was reached when the compressor inlet pressure was 1 bar. Smallest increment was occurred at expansion valve inlet.

Figure 12 shows the relationship of the lower stage inlet pressure to the temperature distribution in the lower pressure stage evaporator at over atmospheric pressure. The temperature increases equivalent to the lower stage compressors inlet pressure.

Figure 13 show that the lowest temperature which can be obtained by this cascade refrigeration system arrangement is down to −85℃. This

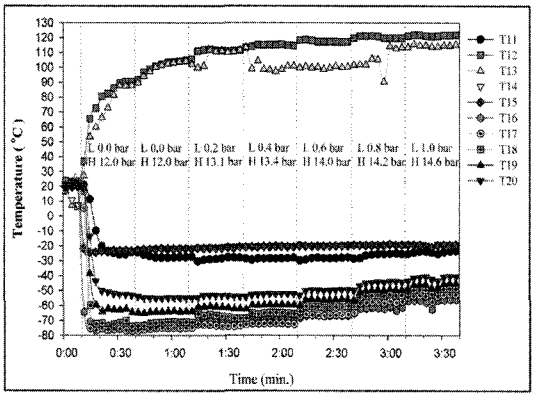


**Fig. 12** Temperature distributions of low pressure Stage, at inlet pressure of low-pressure compressor : 0.0 to 1.0 bar

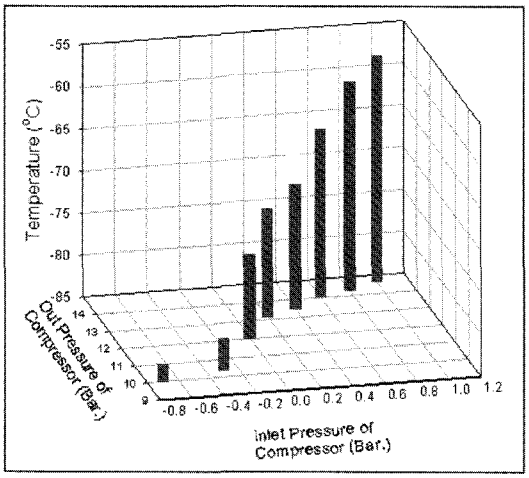


**Fig. 13** Temperature distribution in the low-pressure stage evaporator inlet as function of the low-pressure stage inlet and outlet pressure

temperature is reached when inlet pressure of the low-pressure compressors is −0.7 bars and the compressors outlet pressure is 9.9 bars. Thus, the temperature distribution has equivalent relationship with inlet pressure and compressors outlet pressure of the low-pressure stage compressors. Fig. 13 summarize relationship of the low-pressure compressors inlet pressure and outlet pressure to the super-low temperature characteristics.

## 4. Conclusion

The inlet and outlet pressure of low-pressure stage compressors to the overall temperature characteristics of cascade refrigeration system has been observed.

The main experiment result are as following :

(1) The pressure adjustment at the outlet pressure of low-pressure stage compressor affects to the temperature distribution. More higher the compressor outlet pressure, more low temperature in the low-pressure stage evaporator can be reached.

(2) The most lowest temperature obtained cascade inlet compressor of vacuuming pressure and outlet compressor 10 bars.

(3) Yet, improper pressure adjustment in the compressor inlet can cause temperature and pressure fluctuation in the compressor and temperature distribution in the cascade refrigeration.

(4) In case of compressor inlet pressure of low-pressure stage, more low the low-pressure inlet, more low temperature of the low-pressure stage evaporator temperature can be reached.

(5) The major obstacle to reach this super-lower temperature is the compressor limitation. The vacuum pressure can cause compressor oil to evaporate thus endanger the system itself. Consequently, careful attention of vacuum controlling is required.

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