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Water Cooling Characteristics in an Enclosed Vacuum Tank by Water Driven Ejector

Hyo Min Jeong, Han Shik Chung*
School of Mechanical & Aerospace Engineering, Institute of Marine Industry, Gyeongsang National University, Gyeongnam 650-160, Korea
Kang Youl Bae
Boo 1, Kaong Plant Co., Ltd., 6 Floor, Hwoiwon Credit Union B/D, 670-6, Hwoiwon-Dong, Masan, Gyeongnam, Korea
Se Hyun Kim, You Sik Shin
Graduate School, Department of Mechanical and Precision Engineering, Gyeongsang National University, Gyeongnam 650-160, Korea

The general cooling tower is a device for cooling water in industrial condensers or heat exchangers. The present cooling towers have defects with noises, complicated structures and environmental problems. This paper focuses on a new water cooling system using the latent heat of evaporation in an enclosed vacuum tank and a water driven ejector system. Several experiments were carried out to improve high vacuum pressure and water cooling characteristics. The ejector performance was tested with various water temperatures. Based on the vacuum pressure of the water driven ejector, the water cooling characteristics were investigated for the condensed and vaporized air and the effect of increased evaporating surface area in an enclosed tank.

Key Words : Cooling Tower, Water Driven Ejector, Vacuum Pressure, Latent Heat of Evaporation

Nomenclature

A : Cotton area [m^2]
L : Tank volume [L]
P : Pressure [mmHg. abs.]
Q : Flow rate [L/min.]
RT : Refrigeration Tonnage
T : Temperature [℃]

Subscripts

A : Air in enclosed tank
hc : Heat exchanger for condensing
he : Heat exchanger for ejector water
in : Initial value
E : Ejector
p : Ejector pump
r : Area ratio
T : Enclosed tank
w : Water in enclosed tank

* Corresponding Author,
E-mail : hschung@gsnu.ac.kr
TEL : +82-55-640-3185; **FAX** : +82-55-640-3188
School of Mechanical & Aerospace Engineering, Institute of Marine Industry, Gyeongsang National University, Gyeongnam 650-160, Korea. (Manuscript **Received** December 26, 2003; **Revised** October 23, 2004)

1. Introduction

Cooling towers are commonly used to dissipate heat from water-cooled refrigeration, air-conditioning, and industrial process systems. The heat that is generated by these systems must be removed. Water is commonly used as a heat transfer medium to remove the heat from industrial refrigerant condensers or heat exchangers. Water utility bills become expensive because of increased water supply and disposal costs. Similarly, cooling water drawn from natural sources is unavailable due to environmental disturbances.

In a once-through system, the water consumption rate of the cooling tower is about 5%, and the re-circulating flow rate as described in the design handbook(SAREK, 1987) is 780L/RT/hr. Therefore, as the cooling tower capacity is increased, the water consumption rate is proportionally increased and causes environmental problems, such as Legionella disease, by the vaporized water drift from cooling towers.

In the past, cooling towers were not important to refrigerating systems because the power consumption rate in the cooling tower is below 2%. We have to focus on the cooling tower with other viewpoints. The cost of electric power rises 10% or more as the cooling water temperature rises by 1.5℃. When the water returns from the cooling tower, the temperature of the water is about 31~32℃. The temperature of the water that flows into the cooling tower is about 37℃. Thus, the temperature difference for the standard cooling tower system is estimated at 5~6℃.

The present cooling towers are summarized as two types. Namely counter flow and cross flow, reported Chu et al.(1999) and Kim et al.(2000). Most of the present cooling towers utilize the effects of latent heat of evaporation and sensible heat by the atmosphere. This system poses the following dilemmas. First, the cooling rate is strongly influenced by atmospheric conditions. Second, present cooling towers need a great deal of added health and safety features to prevent Legionella disease. Third, electrical failure and energy consumption are high because of the large fans, making the system very complicated. Fourth, the external appearance is not appealing. This system generates a great deal of noise because it is constructed outside of buildings. There are three kinds of ejectors in industrial processes. These ejectors are classified by the driving fluids used such as air, steam or water. The water driven ejector is most commonly used because of its simple design and cost effectiveness. The water driven ejector has been utilized for the following two theories. (Kim, 2000, Simizu, 1987); one is the transportation of materials such as a bilge discharge, brine discharge in fresh water generators and fish pumps, etc., The other is for making the vacuum pressure in an enclosed tank (Kim, 2001). Most research focused on the inside flow of an ejector by the numerical (Choi et al., 2001) and experimental (Kim et al., 2002 ; Lee et al., 2001) analysis.

In this paper, we focused on the water cooling characteristics using an enclosed vacuum tank and water driven ejector for replacing present cooling tower systems.

The proposed water cooling system is operated by the latent heat of evaporation , thus this system needs a vacuum pressure to make the water evaporate in the enclosed tank. The effects of the cooling water are dependent on the vacuum pressure and the ejector plays an important role in preserving the evaporating pressure. The main purpose of this study is to experiment with ejector performance at various driving temperatures and to study the characteristics of water cooling in an enclosed vacuum. Condensation of the vaporized air and the effect of an increased evaporating area were also studied.

2. Experimental Descriptions

The cooling effects are dependent on the vacuum pressure, thus the vacuum pump has to achieve the pressure of evaporation. As the general vacuum pump is designed for high vacuuming in a small space, the ejector pump system is more suitable than the vacuum pump. In this paper, the water driven ejector pump system is proposed for vacuuming in the enclosed tank.

Figure 1 shows the details of the ejector. This system consists of three main parts : the nozzle, straight pipe and diffuser. The nozzle diameter is 5.7 mm and the straight pipe diameter is 15 mm with lengths of 65 mm each. The length of the diffuser is 101 mm and the diffuser angle is 6.2°.

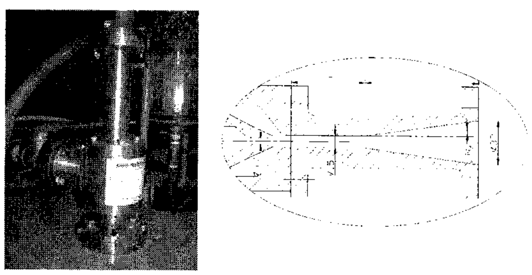
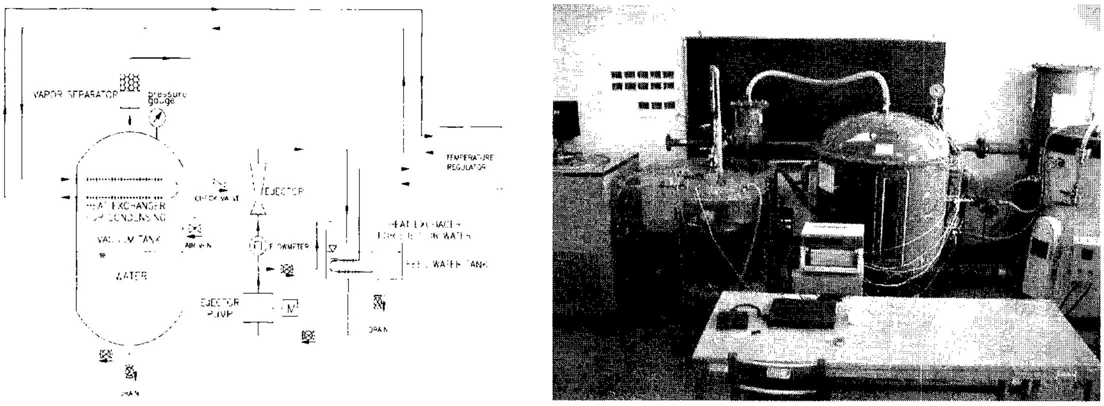


Fig. 1 Drawings and photo of ejector.



(a) (b)

Fig. 2 (a) Schematic diagram of experimental setup (b) Photography of experimental setup

Figure 2 shows the experimental apparatus to measure the effect of vacuum levels in the enclosed tank. The designed vacuum chamber has a capacity of 568L and the inside air of the vacuum tank is evacuated by a water driven ejector. The water that passes from the ejector is re-circulated through the feed water tank into the ejector pump. The vacuum tank achieves a low pressure state according to the ejected air. Therefore, the water in the vacuum tank achieves an evaporation condition faster than an atmosphere condition, and the water in the vacuum tank is cooled down. The ejector pump has a float type flow meter and adjusting valve. The pressure transducer (PSHA-0760HAAJ) was installed on the top of the vacuum tank. The pressure signal is transmitted to a personal computer and data logger (DR130, YOKOGAWA). The flow rates were controlled by a flow rate adjusting valve and were measured by variable area flow meter. The uncertainty in the flow rate measurement was $\pm 1 \sim 2\%$. Temperatures in the feed water tank and enclosed tank for both cooling and heating mediums were measured by means of chromel-alumel thermocouples. The uncertainty in the temperature measurement was with in ± 1℃. The pressure at the top of enclosed tank was measured with pressure transducer. The uncertainty in the pressure measurement was within $\pm 0.15\%$. Two heat exchangers were installed in the experimental apparatus. One was located on the air side in the enclosed tank for condensing the evaporated water. The other was immersed in a feed water tank for cooling the water that is pumped to the ejector. The primary experimental process is carried out for about 6 hours before the main experiment. The initial temperature of the re-circulated water in the feed tank was set to 7.4℃, 13.8℃, 35.5℃ and 49.8℃. The initial water temperature in the enclosed vacuum tank was about 37℃. During the experiment, the ambient temperature was 25℃. The temperature of the two heat exchangers was controlled by a temperature regulator.

3. Results & Discussion

3.1 Effect of ejector water temperature

To achieve cooling water, the water should be in an evaporating condition. This condition can be achieved by vacuuming. The water driven ejector was introduced in this study.

Generally, the vacuum pressure by a water driven ejector is dependent on the flow rate, water temperature, nozzle size and diffuser angle of the ejector outlet, etc. In Fig. 3(a), the flow rate is related to the vacuum pressure. The vacuuming rate is proportional to the flow rate. To get the best vacuum pressure an optimum condition must be achieved. We also focus on the effects of ejector water temperature. Fig. 3(b) shows the vacuum pressure distributions for the various initial temperatures of the ejector water. Because the general water density depends on the temperature. If the density of the working fluid is increased,

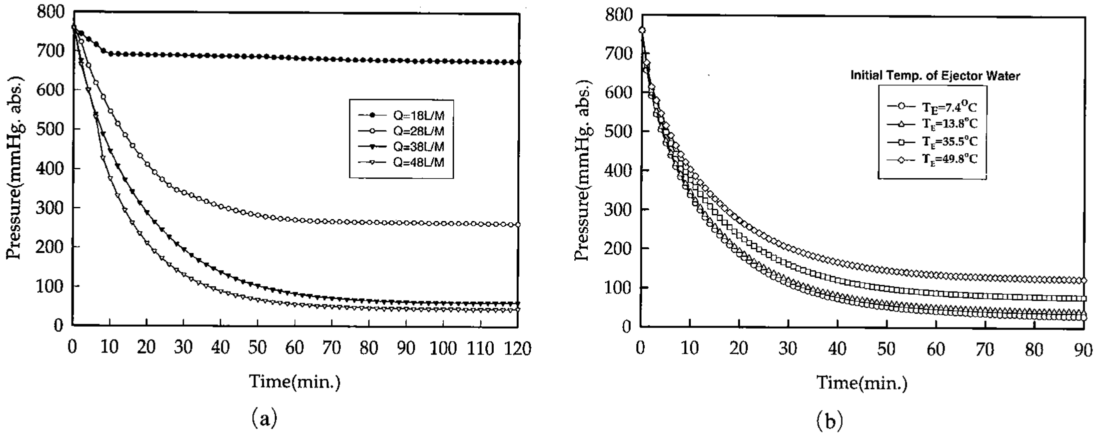


Fig. 3 (a) The vacuum pressure distributions in an enclosed tank for various flow rates into ejector
(b) The vacuum pressure distributions in an enclosed tank for various initial temperatures of ejector

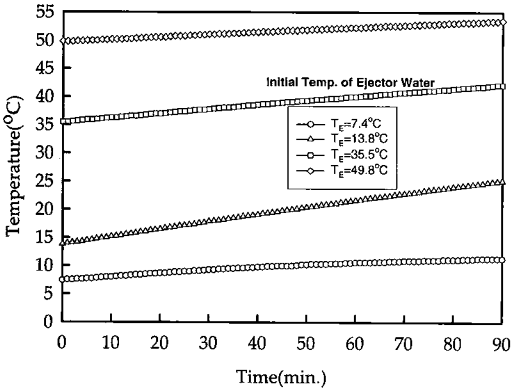


Fig. 4 The temperature variations of ejector water

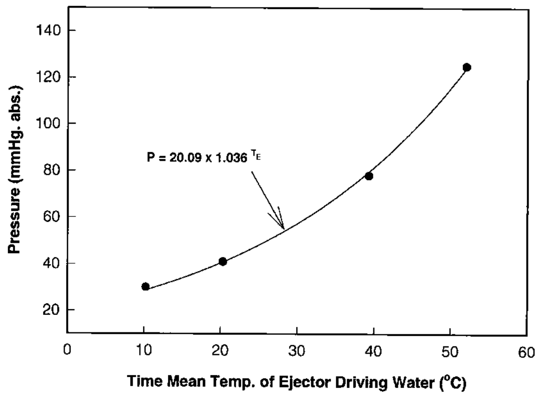


Fig. 5 Relationships between vacuum pressure and mean ejector water temperature

the amount of suction is higher. Therefore, when the pressure inside the tank is dropped the suction is lower.

An empty tank with a capacity of 568L was used in this experiment. The main parameter is the initial temperature of the ejector water. As the initial temperature T_E was low, the enclosed tank pressure had a higher vacuum pressure. This pressure was constant after about 90 minutes. This is why the low water temperature caused a high density suction around the ejector. From Fig. 3 (a) and (b), even if the ejector pump capacity is small, the equivalent vacuum pressure can be achieved by placing water with a lower temperature into the ejector.

Figure 4 shows the temperature variations of ejector driven water in a feed water tank. This temperature increased linearly because the friction is increased in the pipe and ejector.

Figure 5 represents the relationship between vacuum pressure and mean ejector water temperature. The temperatures on the horizontal axis were taken at 90 minutes. In Fig. 4 this is considered a steady state. From this point, the wake temperature through the ejector has a direct correlation to the vacuuming pressure. To get a high vacuum pressure, it is recommended that the low initial temperature be maintained.

3.2 Water cooling characteristics

Lower temperature water flowing into the ejector induces the high vacuum pressure. This means

Table 1 Main experimental parameters for water cooling test

	Type1	Type2	Type3
Enclosed tank volume (Liters)	568	568	568
Filled water and air volume (Liters)	$300L_W$ $268L_a$	$300L_W$ $268L_a$	$300L_W$ $268L_a$
Flow rate into ejector pump, Q_p (L/M)	50	50	50
Flow rate in heat exchanger of ejector water, Q_{he} (L/M)	none	8	none
Flow rate in heat exchanger of condensing, Q_{hc} (L/M)	none	none	5.3

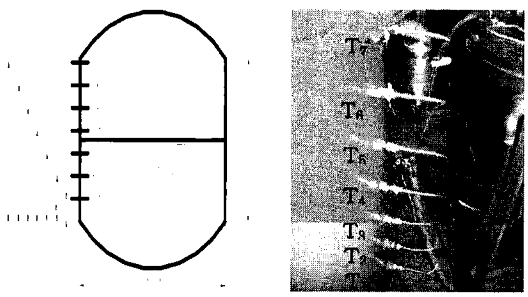


Fig. 6 Schematic diagram and photography of temperature measuring points

that the evaporative condition can be easily obtained. The water under the evaporative condition absorbs the latent heat and will be cooled. In this section, the water cooling characteristics were investigated with several experimental conditions.

The temperature measuring points in an enclosed tank are shown in Fig. 6. The capacity of the empty vacuum tank is 568L. For example, $300L_W$ means the water in the vacuum tank is filled with 300L of water and the remaining air occupied a volume of 268L.

The initial water temperature was set to about 37℃ in this experiment. This temperature was intended as the temperature for a general cooling tower system.

As shown in Fig. 6, the temperature sensors (RTD PT100Ω) T1, T2 and T3 are immersed in the water, and the other temperature sensors T4,

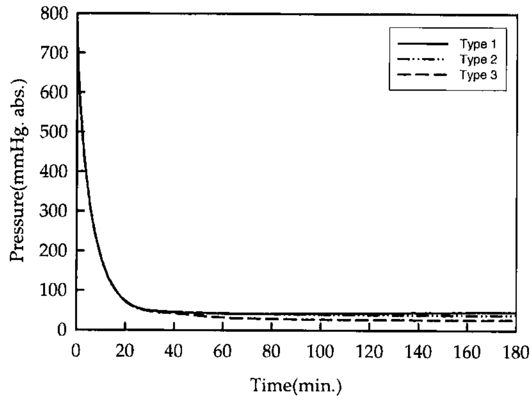


Fig. 7 Vacuum pressure distributions for three types ; Type1, Type2 and Type3

T5, T6 and T7 are contacted with the air in the enclosed tank.

Table 1 shows the parameters for the three types. The experiments were carried out for the effects between Q_{he} and Q_{hc}. The values of Q_{he} and Q_{hc} are the ejector water flow rate in the heat exchanger of ejector water and the air in the enclosed tank as shown in Fig. 2(a), respectively.

Figure 7 represents the vacuum pressure distributions for the three experiments as shown in Table 1. After 30 minutes, the pressure had an almost steady condition and the pressure values of Type1, Type2 and Type3 were recorded 49.4, 48.8 and 47.6 mmHg. abs., respectively.

These pressure values were gradually decreased to 45, 38 and 26 mmHg. at 180 minutes. Type3 had the highest vacuum pressure, which meant that more cooling water was obtained because of the active evaporated water.

In order to investigate the water cooling effect under vacuum pressure, the following experiment was conducted in the cases of Type1, Type2 and Type3. Figs. 8~10 show the temperature distributions of the enclosed tank and ejector water for each type. In these figures, the black and white symbols are the temperatures of the water and air, respectively. The temperature T_E is the water temperature in the ejector pump line and this water is re-circulated with a closed pipe line. The water temperature had a steep gradient of around 30 minutes. The evaporating condition was reached at this point. From Figs. 8~10, there

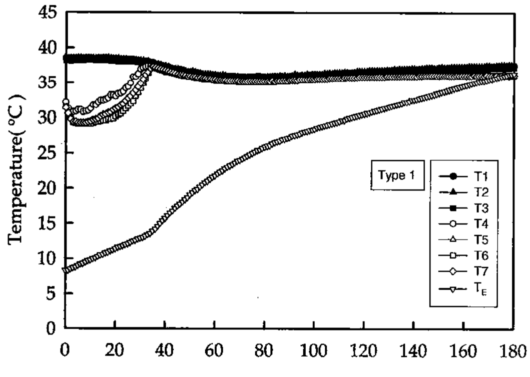


Fig. 8 Temperature distributions of enclosed tank and ejector in case of Type1

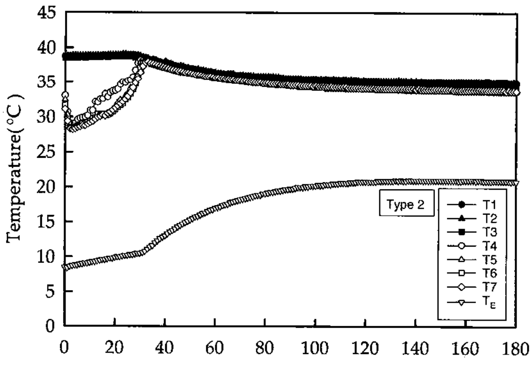


Fig. 9 Temperature distributions of enclosed tank and ejector in case of Type2

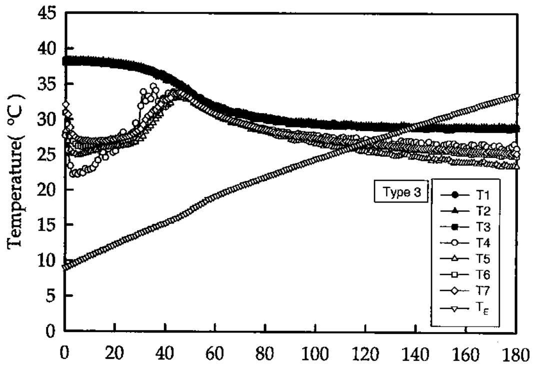


Fig. 10 Temperature distributions of enclosed tank and ejector in case of Type3

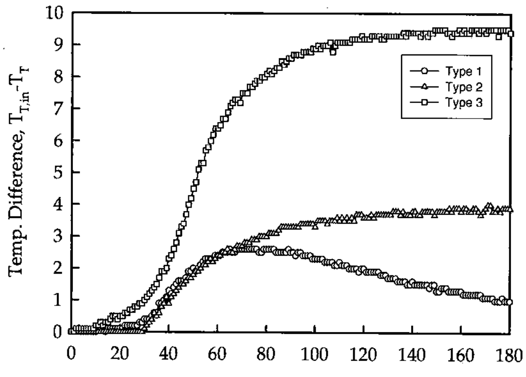


Fig. 11 Temperature difference distributions in enclosed tank

is no temperature difference among T1, T2 and T3, thus the water temperature can be estimated as the same. In cases of less than 30 minutes, the temperature difference of T4, T5, T6 and T7 are strongly affected by the temperature of the surface water in the vacuum tank. Therefore T4, T5, T6 and T7 are in an unstable condition and have a temperature differences. The initial temperature of the air was gradually increased until 30 minutes. Because the general evaporating conditions for water is 50 mmHg. abs.. under 38℃, the pressure value at 30 minutes has reached the evaporating condition. This evaporative phenomena can be observed from the abrupt decreasing temperature as shown in Figs. 8～10.

The tendency of air temperature distributions coincided with water temperatures after 30 minutes. This is why the latent heat from water is dominant on the air side. The temperature differences between water and air were not apparent. However, in the case of Type3 shown in Fig. 11, the air temperature was lower than the water. This is due to the air condensation by the heat exchanger which was installed in the enclosed tank as shown in Fig. 2.

The ejector water temperature was almost linearly increased except in Type2 because the cooling water was supplied in Type2 only.

Figure 11 shows the variations of the temperature difference in the enclosed tank. The vertical axis values, T_T,T_{T-in} represent the temperature differences between the initial water temperature of

Table 2 Main experimental parameters for increasing an evaporating area

	Type4	Type5	Type6
Enclosed tank volume (Liters)	568	568	568
Filled water and air volume (Liters)	$200L_W$ $368L_a$	$200L_W$ $368L_a$	$200L_W$ $368L_a$
Flow rate into ejector pump, Q_p (L/M)	50	50	50
Approximate initial ejector inlet temperature (℃)	10	10	10
Flow rate in heat exchanger of ejector water, Q_{he} (L/M)	none	none	none
Flow rate in heat exchanger of condensing, Q_{hc} (L/M)	5.3	5.3	5.3
Sheets of cotton	none	5	13
Evaporating area ratio, A_r	1	1.6	2.4

38℃ and the T1 temperature. The largest cooling water effects were obtained in the case of Type3. When the experimental time is 180 minutes, Type3 had the lowest vacuum pressure of about 35℃ of ejector water as shown in Figs. 7 and 10. From these results, the low ejector water temperature can be attributed to the high vacuum pressure. This is effective within the limit ejecting effect get started. The ejector water temperature is not significant at the beginning of the steady pressure condition, and it is recommended that the initial ejector water is below 10℃ in this experimental system. There are two factors for making vacuum pressure high, namely the influences of the initial ejector water temperature and flow rate in which the water flows into ejector.

Comparison between the three cases reveals that the air condensing effect is closely related to the water cooling characteristics more than other factors as shown in Fig. 11.

3.3 Cooling effect for increasing an evaporating area

Water particles have an interactive attraction among water molecules and when the partial pressure is dropped under the condition of evaporation, evaporation is started. Water evaporation is generated from surface water when the evaporating pressure was reached. There are many methods to get a water cooling effect; the method for increasing an evaporation area by inserting cotton microfibers was introduced in this paper.

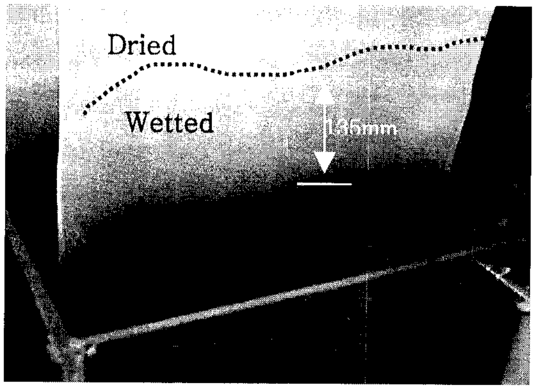


Fig. 12 Photo of hygroscopic test under atmospheric pressure

Figure 12 shows a photo of a hygroscopic test under the atmospheric pressure before it was installed into the enclosed tank. The wetted length to gravitational direction was about 135 mm by capillary attraction and cotton microfiber of 450 mm × 175 mm was used in the enclosed tank.

Table 2 represents the experimental parameters to investigate the cooling effects by increasing the evaporating area of the water surface in the enclosed tank.

The evaporating area ratio, A_r, was defined as the ratio of total evaporating surface and the circular area of the water surface. For example, $A_r = 2.4$ means that the total evaporating area is 2.4 times greater than in Type4 where cotton was not inserted into the tank.

Figures 13～15 shows the temperature distributions of the enclosed tank and ejector water in $A_r = 1$, 1.6 and 2.4. The temperature sensors T1 and T2 are immersed and the others are contacted with the air. The general temperature distributions present a similarity to Fig. 10 except in air side temperatures. These air side temperatures from T3 to T7 in Figs. 13～15 are lower than

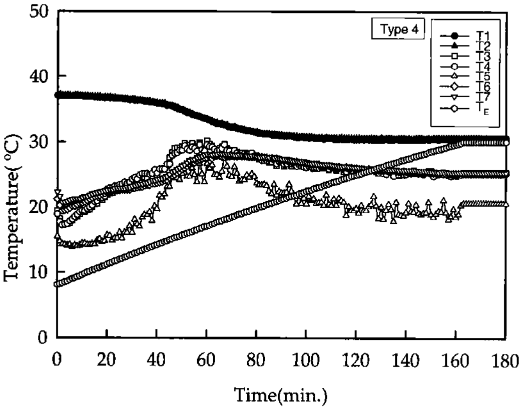


Fig. 13 Temperature distributions of enclosed tank and ejector in case of Type4

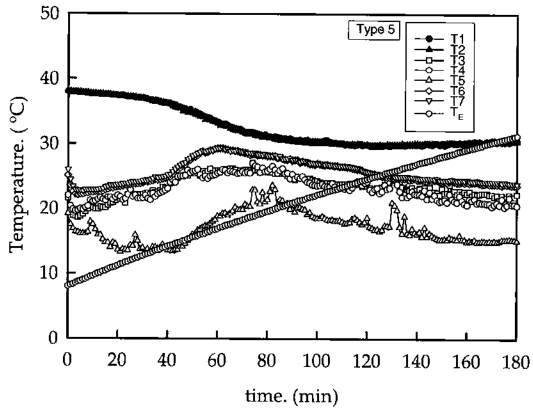


Fig. 14 Temperature distributions of enclosed tank and ejector in case of Type5

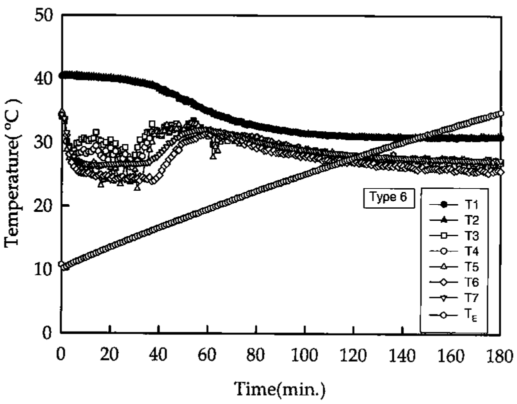


Fig. 15 Temperature distributions of enclosed tank and ejector in case of Type6

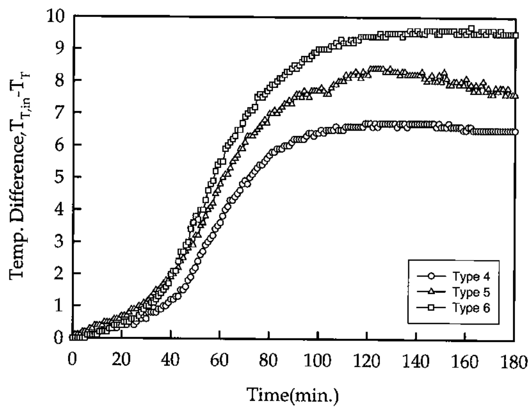


Fig. 16 Temperature difference distributions in enclosed tank

Fig. 10. More evaporated water is cooled by the heat exchanger in the air side. This evaporated water has a larger heat capacity than the case of Fig. 10, and the ejector water temperature had an almost linear increase because of frictional heat generated in the ejector water line.

Figure 16 shows the distributions of the temperature differences in the enclosed tank. The best water cooling effects were obtained in Type6. When the experimental time is 100 minutes, all of the cases have a stable and steady heat exchange. These results lead us to conclude that the improvements of the water cooling characteristics can be achieved by increasing water surface in the evaporation area.

4. Conclusions

In this paper, we proposed a water cooling system by latent heat of evaporation. This system consists of the enclosed vacuum tank and water driven ejector system. From an experimental result, the conclusions are summarized as follows :

(1) The water temperature being cooled in a present cooling tower system is about 37℃. To get an advanced cooling effect from this temperature, we introduced the forced evaporating system which operates under vacuum pressure.

In this paper, the cooling effects and the vacuum pressure for getting latent heat of evaporation were obtained by ejecting air in an enclosed tank.

(2) At lower water temperatures the ejector produced a higher vacuum pressure, the initial temperature for the water ejector is important. It is desired to maintain the initial temperature and not to exceed 10℃ in this experimental system. The relationship between vacuum pressure and ejector driving water were represented as $P = 20.09 \times 1.036^{T_E}$, where P and T_E mean the enclosed tank pressure and ejector driving water temperature.

(3) Comparisons between the several experimental cases reveals that the air side condensing in the enclosed tank is more important to the water cooling characteristics than the other factors. The improvements of water cooling characteristics can also be achieved by increasing the evaporation area of the water surface. The cooling rate was increased by 10% in case that the evaporating area ratio is 2.4.

(4) By increasing the ejector pump flow rate the time to reach an evaporation condition can be shorter and higher vacuum pressure is easily obtained.

Acknowledgements

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