Cooling Technology for Global Vending Machine Installed in High-Temperature High-Humidity Environments

MURASE, Takao*

ABSTRACT

We have been working on the development of a global vending machine capable of operating in environments with an ambient temperature of 40 °C and relative humidity of 75% in consideration of the maximum temperatures and humidities of the major cities in China. In addition to achieving our goal of supporting increased ambient temperatures, we have also developed an efficient operating control technology, as well as a heat insulating and cooling technology for efficiently cooling increased heat loads. With regard to the impact of frost that forms on evaporators in high-temperature and high-humidity environments, we have focused on evaporation temperature setting levels based on the result of observing the frost formation process, and by readjusting the setting levels we have been able to control the amount of frost formation. These measures have enabled us to achieve a reduction in the required cooling capability and a shorter initial cooling time even in high-temperature high-humidity environments.

1. Introduction

According to a survey conducted by the Japan Vending Machine Manufacturers Association, there were 2,568,600 beverage vending machines installed at locations throughout Japan as of the end of 2014, which is a 0.9% decrease from the previous year. Major reasons for the decrease of installations include a reduction in sales due to price increases following the increase in consumption tax, as well as a reduction in sales of canned coffee resulting from the increase in popularity of coffee beverages sold at convenience stores. On the other hand, subway stations, office buildings and factories in major Chinese cities have seen an increase of about 70,000 to 80,000 installations, and it is expected that this number will continue to rise in the future.

Fuji Electric has developed a global vending machine for installation in high-temperature high-humidity environments to support the development of growing overseas markets such as China. This paper describes the unit's cooling technology.

2. Development Background

In major Chinese cities, such as Shanghai, Hangzhou and Guangzhou, maximum temperatures get as high as 40 °C annually, making these high-temperature environments even hotter than that of Japan. Japan has its high-temperature environmental condition set at 32 °C and, as a result, has conventionally never had the need to verify operations in high-temperature high-humidity environments exceeding 40 °C. The low-temperature environmental condition (temperature of 5 °C) is the same as Japan, and thus verification has already been completed for this operation specification.

Development of vending machines for expansion into global markets such as China requires specifications that take into consideration high-temperature high-humidity environments.

3. Development Goals and Challenges

3.1 Challenges related to high-temperature high-humidity environments

The cooling capacity of vending machines is evaluated by the amount of thermal energy absorbed from inside the storage unit per unit of time. The amount of thermal energy is determined by the difference between an ambient or product temperature and a target temperature. A larger difference in temperatures indicates a larger amount of absorbed thermal energy, and as a result, requiring a high cooling capacity.

Furthermore, since thermal energy is proportionally distributed based on the time it takes until product cooling is completed, shorter target times for completion will result in higher cooling capacity required per unit of time.

Figure 1 shows the relationship between the time it takes for cooling to complete and the required amount of cooling capacity. In Japan, a period of 24 hours at an ambient temperature of 32 °C has been established as the standard for completion of cooling when cooling from the initial state, in which ambient and product temperatures are equal. A change in ambient temperature from 32 °C to 40 °C to accommodate the Chinese market will require an increase in cooling capacity of 1.4 times as a result of the increase in thermal energy due to the temperature difference.

Moreover, in consideration of the cooling that is

---

* Food and Beverage Distribution Business Group, Fuji Electric Co., Ltd.

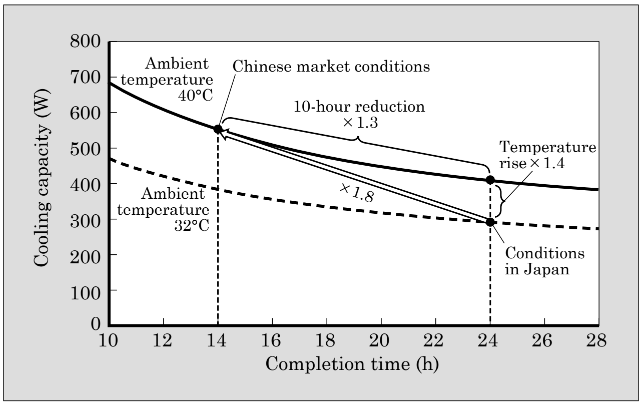

Fig.1 Relationship between completion time and required cooling capacity

required to restore the system to its stable state of operation after replenishing the unit with new product (restoration of cooling after replenishing), it is demanded that this restoration time be as short as possible to prevent loss of sales owing to the unit being in vending standby mode while it cools the replenished product. The Chinese market is requiring that the time necessary for the restoration of cooling after replenishing all of the unit's product be within 14 hours, which is 10 hours shorter than the 24 hours required by the Japanese market. In order to shorten the time for completing cooling by 10 hours, a cooling capacity of 1.3 times is required to implement initial cooling under the same ambient temperature conditions.

As a result, a restoration of cooling after replenishing that takes 14 hours at an ambient temperature of 40 °C requires a cooling capacity 1.8 times greater than the standard used in the Japanese market. Operation under the high ambient temperature results in decreased efficiency for the refrigeration unit, and this, in turn, causes a decline in cooling capacity. In order to secure high-efficiency cooling, measures need to be properly implemented with respect to heat loads.

Furthermore, even when relative humidity is the same, there is a greater amount of water vapor in the air when the ambient temperature is higher. As the temperature inside the storage unit decreases, water vapor condenses and this generates dew and frost. This dew and frost attaches to the surface of the fins of the evaporator (heat exchanger for cooling), and this reduces cooling efficiency. As a result, there needs to be some measures for preventing the adverse impact of this phenomenon.

3.2 Goals

In proceeding to develop a global vending machine, we had to establish design values for high-temperature and high-humidity ratings capable of meeting the environmental conditions of an ambient temperature of 40 °C and a relative humidity of 75%, which is an increase over the Japanese standard of an ambient temperature of 32 °C and relative humidity of 65%, while at the same time aiming to complete the restoration of cooling after replenishing within 14 hours, and working to improve cooling performance during initial cooling and restoration cooling. To accomplish this, we set forth the following 3 tasks:

(a) Establishing heat load assumptions, and securing insulation and cooling performance
(b) Reduction in initial cooling time based on optimized operation control
(c) Measures against frost

4. Characteristics of High-Temperature High-Humidity Environment Technology

4.1 Establishing heat load assumptions, and securing insulation and cooling performance

The required cooling capacity for the vending machine is determined by Formula 1.

Required cooling capacity =
outside invading heat + product heat load[*1] ...(1)

To increase the required cooling capacity, a larger compressor or heat exchanger could be used, but since this will increase power consumption, it is not a desirable option. On the other hand, if the cooling heat load of the "outside invading heat" and "product heat load" is properly controlled, the required cooling capacity can be reduced, and this will make it possible to achieve a more efficient cooling system. We will now introduce 2 specific measures.

(1) Measures against outside invading heat

Figure 2 shows measures against outside invading heat. Heat that invades the storage unit from the outside increases in proportion with the difference in temperature inside and outside the storage unit. If an invading heat of 32 °C is taken as a base equal to 100, raising the ambient temperature from 32 °C to 40 °C will likewise increase invading heat by 28%.

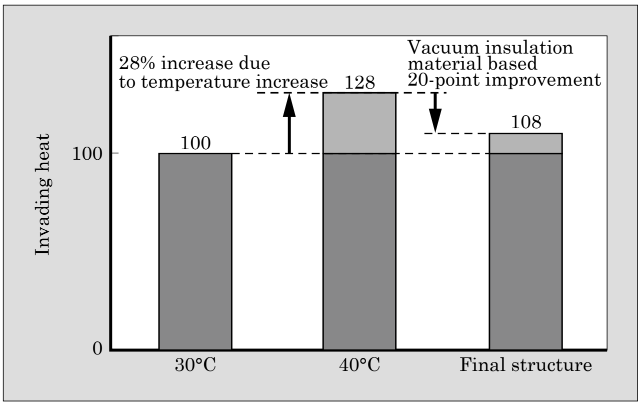

Fig.2 Measures against outside invading heat

[*1] Product heat load: This refers to the sum total of thermal energy that needs to be absorbed when cooling products inserted in the storage unit in order to reach the appropriate temperature for dispensing.

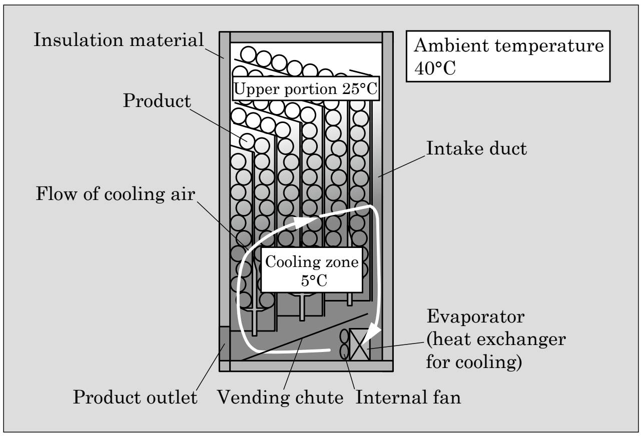

Fig.3 Overview of zone cooling

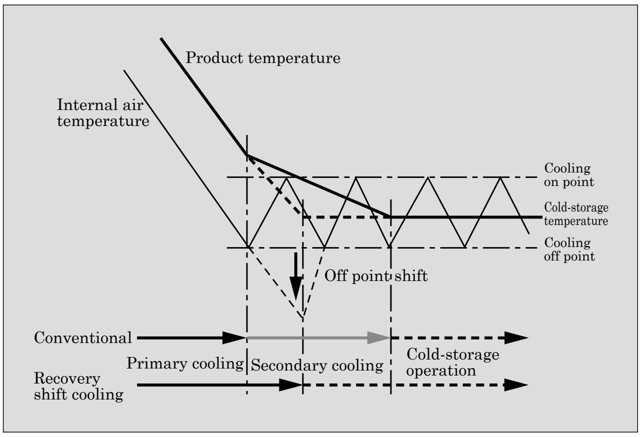

Fig.4 Overview of recovery shift cooling

Our current development makes use of vacuum insulation material for the heat insulation structure, resulting in a 20 point improvement in the heat insulation effect under a 40 °C environment. As a result, the increase in invading heat due to changes in ambient temperature is suppressed between 8% and 28%, and this, in turn, has suppressed the required cooling capacity.

(2) Zone cooling based product heat load measures

Figure 3 provides an overview of zone cooling. The required cooling capacity can be reduced by only cooling the portion of beverages subsequently available for purchase instead of the entire storage unit.

Our analysis of sales patterns in the Chinese market showed that it is possible to maintain proper cooling for beverages by cooling up to the 4th beverage in queue.

Our current development circulates cooling air in a limited zone that includes up to the 4th beverage in queue from the bottom. Zone cooling minimizes the product heat load to limit the number of products applicable for cooling, and this effectually reduces the required cooling capacity needed in the cooling system.

4.2. Reduction in initial cooling time based on optimized operation control

(1) Recovery shift cooling

Figure 4 provides an overview of recovery shift cooling. On-off control for the cold-storage operation has conventionally implemented cooling control based on the air temperature inside the storage unit as the cold-storage temperature level, and not based on the actual product temperature. This type of implementation initially cools the air temperature inside of the storage unit as opposed to the product temperature, and as a result, on-off control takes place before products reach their cold-storage temperature. Since secondary cooling is initiated during intermittent operations, the rate of product cooling is delayed, and the time it takes for products to reach their cold-storage temperature is prolonged.

Recovery shift cooling aims to reduce the time required in lowering product temperature to the cold-storage temperature by adding a control function for shifting down the on-off control temperature level during primary cooling when cooling begins. This type of control deliberately delays the detection of the off control when lowering the air temperature, enabling primary cooling to continue, and thus shortening the amount of time required in reaching the product cold-storage temperature. Recovery shift cooling reduces the time for reaching the cold-storage temperature to 2 hours and 20 minutes, which is an improvement over the conventional time of 3 hours.

(2) Shortening the defrosting period

Figure 5 shows a psychrometric chart. Assumed environmental conditions include a high-temperature high-humidity environment with an ambient temperature of 40 °C and relative humidity of 75%. The difference of the amount of water vapor between this environment and a stabilized cooling environment of 3 °C/95% is nearly twice that of the conventional standard of 32 °C/65%. A sufficient drop in internal temperature results in the water vapor inside the storage unit becoming frost that adheres and grows on the evaporator, instead of being discharged as drain water.

This phenomenon of frost formation obstructs the air-flow passage and decreases the heat-exchange

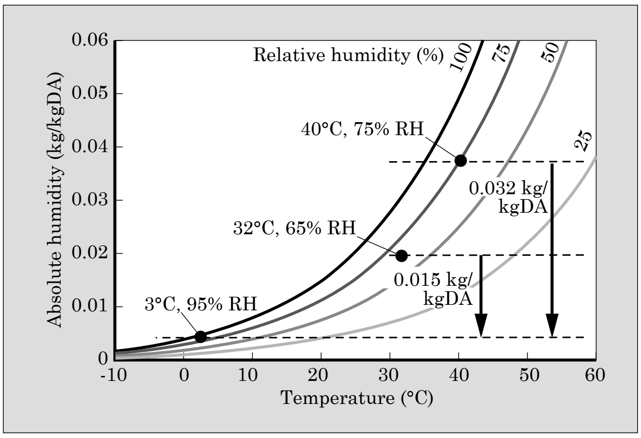

Fig.5 Psychrometric chart

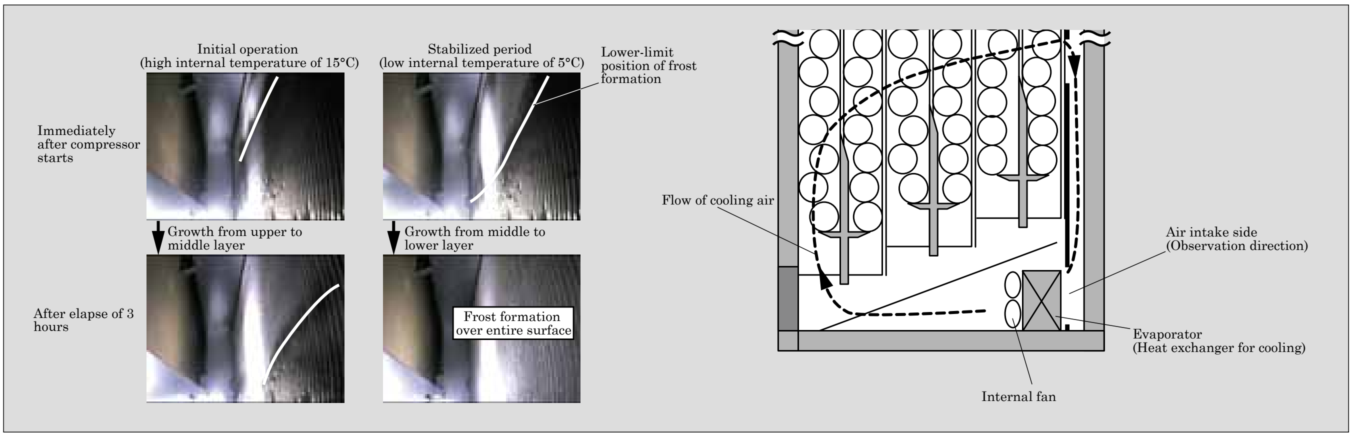

Fig.6 State of growth in frost formation on evaporator

efficiency of the evaporator, resulting in a state in which a sufficient cooling capacity cannot be attained. Furthermore, if freezing continues due to blockage created from frost located between the fins, the evaporator will stop functioning and this will prevent cooling inside the storage unit. Moreover, the amount of time required to stop cooling to implement defrosting by melting the frost is extended in proportion with the growth of the frost, and since the compressor will be stopped during this period, cooling will not be implemented inside the storage unit.

In order to suppress the amount of frost formation, the interval between defrosting operations had to be adjusted to shorter cycles, which means that defrosting will take place more frequently. By doing this, it has become possible to suppress growth in frost formation and prevent evaporator blockages due to frost, thus enabling stable cooling operations for the unit.

4.3 Measures against frost

(1) Verifying the growth in frost formation

We found that severe growth of frost formation occurs not on the exhaust side of the evaporator, but on the air intake side. Thus, we decided to install a compact camera for observing the state of the air intake side at all stages of operation including initial operation and stabilized operation. Figure 6 shows the state of growth in frost formation for the air intake side of an evaporator.

We learned that frost consistently forms on the upper portion (near the refrigerant inlet) even when the temperature inside the storage unit during initial operation is relatively warm (15 °C or higher). This is because frost begins to form when the surface temperature of the evaporator drops below freezing.

With regard to the evaporator, the lowest temperature occurs in the upper portion near the refrigerant inlet, and in contrast to this, temperature increases while moving toward the lower portion outlet. When both the temperature inside the storage unit and the temperature of the intake air are high, heat exchange is implemented and a state of high overheat[*2] will occur, resulting in frost formation being limited to only the upper portion.

We were able to verify that lowering the temperature inside the storage unit to reduce overheat will cause the surface temperature of the evaporator to become gradually uniform with respect to the upper portion, and this temperature change is directly related to the expansion in the range of growth of frost formation. When frost is pervasive over the entire air intake surface, air flow will decrease. This also further accelerates the forming of frost, leading to blockage.

Once a state of blockage occurs, air circulation will be lost and heat exchange will not be implemented until defrosting takes place. During defrosting when the frost is being melted, the temperature of the evaporator will be maintained at 0 °C. The duration of the melting is proportional to the amount of frost formation, and recovery of operation is therefore delayed and temperature rises inside the storage unit. Furthermore, when the refrigeration unit is forced to stop due to defrosting, the frost will melt. However, not all of the melted frost will become drain water to be discharged to the outside of the storage unit during stabilized cycle operation, and a portion of it will remain in the storage unit as water vapor. In addition, we observed that this water vapor will freeze as the temperature of the evaporator decreases after the restart of operation, causing the former state to occur again.

(2) Lower limit control of the evaporation temperature

---

*2: Overheat: The refrigerant flowing inside the evaporator absorbs heat and successively changes to the state of evaporation. During this process, flow continues with fluid and evaporation being mixed, while temperature remains constant at the evaporation temperature. When all is evaporated, saturated vapor is generated, and as heat absorption continues, the temperature will rise once again. The value indicating the temperature rise from the evaporation temperature is referred to as overheat.

As mentioned in the previous section, we observed that the formation of frost on the evaporator that accompanies a decrease in the circulating air temperature inside the storage unit will grow from the upper portion to the bottom portion and eventually result in blockage, and that defrosting alone is insufficient to limit the amount of frost formation.

In general, the most effective method of implementing heat exchange for the evaporator is to utilize latent heat, and it is desirable to have stable operations in a state of small overheat. Therefore, it is effective to implement cooling inside the storage unit at an evaporation temperature that does not cause severe growth in the formation of frost, and it is considered that the most important factor in determining the growth of frost formation is the adjustment in the level of the evaporation temperature of the refrigerant.

By verifying growth in the formation of frost, we learned that the temperature with the most rapid growth of frost on the surface of the fins of the evaporator (frost formation temperature) is around −4.5 °C. In conventional units, the evaporator is set to −5.5 °C, and thus internal cooling proceeds creating a stable low temperature for the inside of the storage unit. In addition, frost forms over the entire surface of the evaporator fins, producing an even lower surface temperature for the evaporator. As a result of this, we were able to verify that the surface temperature drops below the frost formation temperature, thus causing growth in frost formation to accelerate and eventually creating a state of blockage for the fins on the air intake side.

Conventionally, heat exchange during cooling was effectively implemented with efficiency proportional to the temperature difference between the evaporation temperature and air intake temperature, but we performed an experiment to verify what would happen when raising the evaporation temperature by 2 °C, thus setting the temperature at −3.5 °C, which is higher than the frost formation temperature. The result of this experiment confirmed that the formation of frost neither spread throughout the entire surface, nor caused blockage of the fins. On the contrary, initial cooling was implemented successfully up to the point of stabilized cooling. Furthermore, our results showed that there was likewise no blockage of the fins during restoration of cooling after replenishing, and that the unit was also able to achieve a shorter completion of cooling time. This result was achieved because the amount of frost formation was decreased, while the heat exchange efficiency of the evaporator was comparatively increased.

Based on the results of this experiment, we readjusted the evaporation temperature level to -3.5 °C. By suppressing the lower limit of the evaporation temperature, we were able to reduce the amount of frost formation.

4.4 Evaluation results

As mentioned thus far, we implemented proper control of the cooling heat load, optimized operation control and carried out measures against frost formation to meet environmental conditions that included an ambient temperature of 40 °C and relative humidity of 75%. We were able to complete the restoration of cooling after replenishing in 13.5 hours, thus beating our target of 14 hours.

5. Postscript

We have successfully developed a cooling technology for global vending machines that is compatible with the high-temperature high-humidity environments characteristic of our target overseas markets.

This development enabled us to identify problems such as the increase in load due to large temperature differences between the ambient temperature and the temperature inside the storage unit, as well as the large impact of the phenomenon of frost formation generated in high-humidity environments. By taking appropriate measures, we have achieved our development goals.

In the future, we plan to continue our development efforts, aiming at not only achieving targets for cooling time under high-temperature high-humidity environments, but also at attaining further enhancements in operation stability and efficiency.

Fuji Electric

Innovating Energy Technology