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**Pilot study on the construction of several temperature-controlled multi-purpose rooms in a disused tunnel**

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**Abstract**

Throughout the world, schemes for putting to use abandoned underground spaces are being pursued. We describe one such pilot scheme involving the utilization of a disused tunnel of an uncompleted railway line that has been revamped as a facility housing temperature-controlled multi-purpose rooms. In all, four rooms were constructed and installed with both indoor and outdoor air conditioning units. Testing of the facility was conducted over a 1-year period to establish operating criteria and to monitor for operating stability. The four rooms were finally maintained at different constant-temperature regimes: cold (5ºC), cool (13ºC), mild (21ºC), and warm (32ºC) with such low power consumption of 0.80 kW because of the nature of the subterranean site. Compared with typical surface facilities, this facility offers an obvious advantage in lower energy consumption. Monitoring of the humidity in the rooms revealed that preventing evaporation from the bare soil surface in the tunnel was the more important factor in controlling humidity in this facility.

The heat transfer analysis of this facility was carried out through the computational analysis using a computational model constructed in this study. Computational analysis showed that the heat insulation property of the tunnel wall was reinforced by prolonged operation and the cost of operating facility became lower with the operation time. In addition, we demonstrated the procedure to estimate the overall heat transmission coefficients of the tunnel wall which was a great help in the design of similar facilities in underground spaces.

The different rooms in the facility are expected to be used for manufacturing fermented foods and drinks depending on temperature and humidity requirements. Not only running costs but also initial costs are expected to be lower than those for surface facilities; for this reason, our system has been demonstrated to be economically viable as well as environment friendly.

*Keywords:* Tunnel, Power consumption, Air conditioner, Multi-purpose utilization, Computational analysis, Overall heat transmission coefficient

## 1. Introduction

Many researchers are in agreement that building underground will give energy savings by reducing heating and cooling loads in comparison with surface structures. Carmody and Sterling (1984) suggested that even at very shallow depths, the ground temperatures seldom reaches the outdoor air temperatures in the heat of a summer day, conducting less heat into the house due to the reduced temperature differential. They examined the influence of site conditions such as climate, orientation, topography, vegetation, etc. on the energy efficiency for constructing and operating the earth-sheltered housings and suggested the procedures for designing cost-effective earth sheltered housings considering the site conditions (Sterling *et al*., 1980, Carmody *et al*., 1985).

The construction cost of underground structures was typically higher than that of surface structures (Carmody and Sterling, 1993). Zevgolis *et al*. (2004) estimated that the cost of creating underground caverns was approximately 60% of the total initial cost. Considering these aspects, it will be cost-effective to construct underground facilities in abandoned underground spaces such as former underground mine openings and disused tunnels of discontinued/uncompleted transportation lines.

Peila and Pelizza (1995) reviewed the utilizations of 84 former underground mine openings around the world. According to their review, one quarter of these are being used for storage of industrial wastes, while 15%, 13% and 11% of these are being used for food storage, mushroom growing, and storage of crude oil, respectively. Underground spaces for food storage and mushroom growing are expected to have an obvious advantage over surface storages because temperature and humidity, which must be properly controlled, are almost constant throughout the year and can be easily controlled.

Both chilled and frozen rooms controlled respectively at 0ºC and –25ºC by using freezers were also constructed in a former mine opening (Park *et al*., 1999). According to their experiments on long-term storage of fruits, fruit quality is not compromised compared with surface storage (Choi *et al*., 2000). They concluded that higher humidities in underground chilled rooms were effective in storing fruit, and therefore suggested the possibility of extended fruit storage through humidity controls.

On the other hand, stored foods may be adversely affected by too much moisture; therefore, waterproofing is one of the most important works in constructing underground facilities. Sterling *et al*. (1978) guides the waterproofing methods for underground facilities and their costs. Zevgolis *et al*. (2004) estimated that waterproofing accounted for approximately 16% of the total initial cost. In addition, insulating works are also important to reduce the unwanted transfer of heat from one area to another (Sterling *et al*., 1978).

From these estimates, cost benefits accrue by taking full advantage of the low cost in construction and operation and by exploiting opportunities presented in using existing underground spaces given adequate water proofing and thermal insulation.

Perfect examples are the many idle tunnels in discontinued/uncompleted lines. These are usually already waterproofed with concrete cladding which has also higher thermal insulation performance than rocks have, and therefore are expected to be easily convertible into storage facilities, more easy than similar sites such as former mine openings which have bare rock walls.

According to the disused tunnels database of UK (2012), there are more than 500 disused tunnels in UK. Japan Railway Construction, Transport and Technology Agency (2012) are inviting transferees of 13 disused tunnels in Japan officially. Although there are few data on the number of disused tunnels in the world, from the examples of those two countries, it is assumed that there are many disused tunnels in the world. For these reasons, we have focused on exploiting an use of disused tunnels in this study.

We have used an idle tunnel, an uncompleted line called Yobuko within the underground rail complex of Karatsu, Saga, Japan. Historically, construction of the Yobuko line began in 1968 and 11 tunnels were constructed with a system length totaling 22.9 km. The construction was canceled in 1980 because of financial difficulties within Japanese National Railways and all the tunnels were abandoned.

The current proposal is to construct several different temperature-controlled rooms in a tunnel to use it for manufacturing fermented foods and/or drinks, which are made through several different temperature stages, by erecting insulation partitions and installing home air conditioners. For example, manufacturing process of dry cured ham usually consists of at least three stages with different temperature: salt-curing at 3-5ºC, drying at 12-14ºC, and aging at 25-30ºC (Arnau *et al.*, 1997). Similarly, temperature through beer brewing process also differs with brewing stages (fermentation or aging) and types of beer (ale or lager). Railway tunnels are usually considered inconvenient structures for conversion to other uses because of their narrow shape; however, for this study, this has been turned to an advantage of this system.

Continual monitoring of the temperature and humidity of each room and the power consumption of the air conditioners enabled the potential and advantages of the utilization of the tunnel on this system to be estimated in this study. In addition, we provided a computational technique which could be helpful for designing similar system in tunnels in this study.

## 2. Methodology

### *2.1 Initial construction of constant temperature rooms in the tunnel*

Fig. 1 shows a location map of the Hatogawa Tunnel in Karatsu. The tunnel itself is 80 m long, with a width of 3.8 m and a height of 5.0 m. The tunnel cuts through the sandstone-dominant formation. The average overburden thickness is approximately 10 m. The tunnel's concrete roof is arched, while the ground is bare unpaved soil. According to the original plan of the tunnel, the thickness of the tunnel lining is 0.6 m. Two side ditches had been excavated in cuts on both sides of the tunnel and these were covered with concrete panels. The tunnel has two entrances, one from the east the other the west, that are closed by stainless doors. By circumstance, we can only enter the tunnel from the west-side entrance; in this paper, for brevity we refer to this as simply the "entrance".

Fig. 2 shows a schematic diagram of constant temperature facility that was constructed in the tunnel. Initially three rooms were constructed from four sheets of insulation paneling made of 50 mm-thick polystyrene foam. These panels were reinforced by aluminum frames and 9.5 mm-thick gypsum board. The gaps between the panels and the tunnel wall were caulked using urethane foam to supplement the insulation between adjacent rooms. The capacity of each of the rooms, beginning with the room near the entrance of the tunnel, was 120 $m^3$, 60 $m^3$, and 120 $m^3$ respectively. Built into each insulation panel was an 0.8 m × 2 m door that contained an insulation material covered with ABS resins.

The first room was equipped with two indoor air conditioning units, typically used in homes, with rated heating capacity of 2.2 kW and installed at height 1 m from the ground surface. The third room was equipped with two outdoor air conditioning units mounted at a height of 3 m from the ground surface. Both the indoor and outdoor units were connected through refrigerant pipes totaling 6 m in length.

The first room was also equipped with a ventilator with rating of 85 $m^3/h$ to extract heat from the first room to the "entrance space", a space between the first room and the entrance. The same type of ventilator was placed in the third room to prevent over-cooling that would cause ice formation on the tunnel walls of the room. Photographs of the rooms constructed in the tunnel are presented in Fig. 3.

### *2.2 Operation*

An initial field trial was started by running both air conditioners in heating mode at a 30°C temperature setting. Heat from the third room was pumped up to the first room during this procedure, thereby cooling the third room and heating the first room. Temperatures in the second room sandwiched between the other two rooms was expected to stabilize somewhere between temperatures of the adjacent rooms. We refer to the three temperature regimes as being warm, mild, and cold.

Running of the ventilator in the first room was controlled by a temperature switch. When the temperature of this room reached the desired 30°C, the ventilator was activated and directed the heated air into the entrance space to maintain continuous heating operation with the indoor units. Similarly, another temperature switch controlled the operation of the ventilator in the third room. When the temperature of this room fell below 4°C, the ventilator was activated forcing warmer air from the innermost space.

Although both temperature and humidity of each room were monitored continuously, we focused particularly on controlling temperature in this study. One goal of this study was to maintain temperature of the rooms within preset ranges of 4-6ºC, 15-20ºC and 30-35ºC respectively, ranges which are often used for fermented food and drink preparations. Equipment arrangements and operating conditions were modified from the original configuration to achieve the goal.

### *2.3 Monitoring*

#### *2.3.1 Temperature and humidity*

Both ambient temperature and ambient relative humidity of the entrance space and each room were monitored and these data were stored every 10 to 30 minutes in data loggers (Ondotori Jr. RTR-53AL, T & D Corp., Japan) that were installed in the entrance space and each room.

#### *2.3.2 Power consumption of the air conditioners*

Power consumption of the air conditioners was monitored by using a watt hour meter (SHW3A, System Artware, Inc., Japan) and the data were stored every 10 to 30 minutes in a computer connected to the meter through the RS-232C.

### *2.4 Computational analysis of heat transfer in this facility*

#### *2.4.1 Computational model of this facility*

A thermal reservoir simulator CMG STARS (Steam, Thermal, and Advanced processes Reservoir Simulator, Computer Modeling Groups Ltd., Canada) was used to estimate the temperature distribution of this facility in this study. CMG STARS has been widely used in petroleum engineering field as a practical reservoir simulator to estimate the oil production by thermal oil recovery. Because the temperature distribution in reservoirs can be estimated easily using this simulator, we selected it for predicting the temperature distribution of this facility.

The computational model of this facility was constructed based on the following concepts.

1) This facility consists of the tunnel inner space, the tunnel wall, the insulation panels, the intake/exhaust of the warm air in the warm room, the intake/exhaust ventilation in the warm room, and the intake/exhaust of the cold air in the cold room. The floor of the tunnel and the sandstone overburden are classified as the tunnel wall because their thermophysical properties are similar to those of concrete which is the material of the tunnel wall.

2) The porosity and absolute permeability of the tunnel inner space are 1.0 and $1.0\times10^{-8}$ $m^2$, respectively. The tunnel inner space is saturated with air.

3) The porosity and absolute permeability of the tunnel wall are 0.0 and 0.0 $m^2$, respectively. There is no fluid phase in the tunnel wall. Only the heat passes through the tunnel wall.

4) The porosity and absolute permeability of the insulation panels are 0.0 and 0.0 $m^2$, respectively. There is no fluid phase in the insulation panels. Only the heat passes through the insulation panels.

5) The warm air whose temperature is 33°C is introduced into the warm room at the intake rate of 22118 $m^3$/day from the intake of the warm air. Both temperature and intake rate of the warm air have been decided according to the actual measured values.

6) The air whose temperature is 17.5°C is introduced into the warm room at the intake rate of 1920 $m^3$/day from the intake ventilation. Both temperature and intake rate of the air have been decided according to the actual measured values.

7) The cold air whose temperature is 3.3°C is introduced into the cold room at the intake rate of 17694 $m^3$/day from the intake of the cold air. Both temperature and intake rate of the cold air have been decided according to the actual measured values.

8) The air of each room is discharged outside of the facility from each exhaust at the same rate as

each intake rate.

9) The room temperatures are decided by the heat transfers between air and air, air and the tunnel wall, and air and the insulation panels.

Fig. 4 shows the schematic diagram of the computational model of this facility. The facility model has open boundaries on all sides and dimensions of 13.0 m width (I-direction), 20.1 m length (J-direction), and 11.0 m height (K-direction). We defined fine grids in the inner space and around the inner space as shown in Fig. 4. The intake and exhaust of the warm air and cold air were located at the blocks adjacent to the insulation panels respectively as shown in Fig. 4. The intake and exhaust of the ventilation air were located on the opposite side of the intake and exhaust of the warm air as shown in Fig. 4.

*2.4.2 Thermophysical properties*

Table 1 shows the thermophysical properties of air, tunnel wall and insulation panel used in the computational analysis. Standard volumetric heat capacity values and standard thermal conductivity values were used in this study except the heat conductivity of air. Air flow in the inner space of this facility is assumed to be turbulent flow which cannot be simulated by CMG STARS. Accordingly, the thermal conductivity value of air was set to 1,000 times as large as the standard heat conductivity of air in this study in order to simulate the large amount of heat transfer in the real inner space caused by the turbulent air flow. Inada and Sterling (1989) reported that rock moisture didn't have significant effect to thermal diffusivity of rock, therefore, effect of the tunnel wall moisture on its thermophysical property was not taken into consideration, that is, thermophysical property of the tunnel wall was assumed to be constant in all seasons in this study.

*2.4.3 Calculation of the heat transmission in the tunnel wall*

Fig. 5 shows the schematic diagram of the heat transfer in this facility. In the warm room, the difference between the heat quantity provided from the intakes and that discharged through the exhaust is expressed by following equation:

$$Q_W = (Q_{ApW} - Q_{AdW}) + (Q_{VpW} - Q_{VdW}) \qquad (1)$$

where $Q_{ApW}$ (J/sec) is the heat quantity provided to the warm room from the intake of the warm air, $Q_{AdW}$ (J/sec) is the heat quantity discharged from the warm room through the exhaust of the warm air, $Q_{VpW}$ (J/sec) is the heat quantity provided to the warm room from the ventilation intake, and $Q_{VdW}$ (J/sec) is the heat quantity discharged from the warm room through the ventilation exhaust. $Q_W$ (J/sec) should balance with the sum of heat quantity discharged from the warm room through the insulation panels and tunnel wall; therefore, the heat quantity discharged from the warm room through the tunnel wall can be calculated as follows:

$$Q_{WdW} = Q_W - Q_{WdM} - Q_{WdIM} \qquad (2)$$

where $Q_{WdW}$ (J/sec) is the heat quantity discharged from the warm room through the tunnel wall, namely the heat transmission in the tunnel wall in the warm room. The $Q_{WdM}$ (J/sec) is the heat quantity discharged to the mild room from the warm room through the insulation panel, and $Q_{WdIM}$ (J/sec) is the heat quantity discharged to the innermost space from the warm room through the insulation panel. The $Q_{WdM}$ and $Q_{WdIM}$ are calculated from following equations:

$$Q_{WdM} = \lambda/d \cdot A_P \cdot (T_W - T_M) \qquad (3)$$

$$Q_{WdIM} = \lambda/d \cdot A_P \cdot (T_W - T_{IM}) \qquad (4)$$

where $\lambda$ (W/m·K) is the thermal conductivity of the insulation panel, $d$ (m) is the thickness of the insulation panel, $A_P$ (m$^2$) is the area of the insulation panel, and $T_W$, $T_M$ and $T_{IM}$ (K) are the mean temperature of the warm room, mild room and innermost room respectively.

In the cold room, the difference between the heat quantity discharged from the cold room through the exhaust and that provided to the cold room from the intakes is expressed by following equation:

$$Q_C = Q_{AdC} - Q_{ApC} \qquad (5)$$

where $Q_{AdC}$ (J/sec) is the heat quantity discharged from the cold room through the exhaust of the cold air, $Q_{ApC}$ (J/sec) is the heat quantity provided to the cold room from the intake of the cold air. $Q_C$ (J/sec) should balance with the sum of heat quantity provided to the cold room from the tunnel wall, next rooms through the insulation panels and the water condensation; therefore, the heat quantity provided from the tunnel wall in the cold room can be calculated as follows:

$$Q_{WpC} = Q_C - Q_{MpC} - Q_{EpC} - Q_{LpC} \quad (6)$$

where $Q_{WpC}$ (J/sec) is the heat quantity provided to the cold room from the tunnel wall in the cold room, namely the heat transmission in the tunnel wall in the cold room. The $Q_{MpC}$ (J/sec) is the heat quantity provided to the cold room from the mild room through the insulation panel, and $Q_{EpC}$ (J/sec) is the heat quantity provided to the cold room from the entrance space through the insulation panel. The $Q_{MpC}$ and $Q_{EpC}$ are calculated from following equations:

$$Q_{MpC} = \lambda/d \cdot A_P \cdot (T_M - T_C) \quad (7)$$

$$Q_{EpC} = \lambda/d \cdot A_P \cdot (T_E - T_C) \quad (8)$$

where $T_E$ and $T_C$ (K) are the mean temperature of the entrance room and the cold room respectively. $Q_{LpC}$ (J/sec) is the heat quantity of condensation which is calculated from following equation:

$$Q_{LpC} = Q_L \cdot Q_d \quad (9)$$

where $Q_L$ (J/g) is the heat of condensation which 2257 J/g was substituted for, and $Q_d$ (g/sec) is the drainage rate of condensed water from the outdoor units which 0.015 g/sec was substituted for.

## 3. Results

### *3.1 Temperature change of each room*

Figs. 6 and 7 show respectively the variation in temperature within each room and power consumption of the air conditioners over the 1-year period after heating operation commenced on the 13th of November, 2008.

Temperature changes in the entrance space indicate the original temperature change in the tunnel in the absence of the refurbishment. Originally, tunnel temperatures varied between 17 and 20ºC over the year. The following modifications were carried out to adjust the temperature of the cold room to 5ºC.

After starting the study, warm room temperatures rose rapidly while those in the cold room fell rapidly becoming stable at 8.5ºC after 7 days of operation. Under these operating conditions, the air conditioners were clearly unable to transfer away from the cold room enough heat and cool to 5ºC. In the warm room, temperature fluctuations between 30 and 31ºC were observed during that period; these fluctuations were evidently caused by repeated and frequent on-off switching of the ventilator. After 15 days of monitoring, we countered this behavior by altering the temperature setting of the ventilator to switch on at 28ºC (point "a" in Fig. 6) so as more heat can be extracted from the warm room. Consequently, temperatures of the cold room fell to between 7.0 and 7.5ºC and stabilized within this range.

After nearly 10 weeks, we moved the cold-room ventilator into the warm room with the intention to extract more heated air there (point “b” in Fig. 6). To ensure proper insulation, the ventilation hole in the cold room was filled with insulation material. After this modification, the temperature of the cold room fell to 5.2ºC and stabilized at this temperature. Temperatures in the mild room also decreased to 18.5ºC from 19.5ºC in conjunction with a decrease in temperatures of the cold room. Because the power of the air conditioners increased to 1.05 kW from 0.90 kW after this modification (point “b” in Fig. 7), we concluded that expanding the ventilation capacity in the warm room was effective in cooling the cold room. These results indicated that the amount of heat extracted from the warm room was of great importance in cooling the cold room.

After 134 days from commencing (point “c” in Fig. 6), a 50 mm thick insulation panel was put over the surface of the door in the cold room and an insulation sheet was also installed at the entrance of the cold room (see Fig. 2-(f)) because heat loss was observed to be taking place, as depicted in Fig. 8 by images obtained by a thermal-imaging camera. As a result of this modification, the temperature in the cold room decreased further (point “c” in Fig. 7) to 4.8ºC with power remaining at 0.90 kW.

After 21 weeks, one ventilator in the warm room was used to force air from the entrance space back into the warm room (point "d" in Fig. 6). The power decreased approximately 10% compared with that before this modification, while cold-room temperatures remained at 5ºC during the 4 weeks after this modification. Cool air had flowed into the warm room from the other two rooms and the air conditioners had been run at higher power to retain the temperature settings before this modification. However, these settings could be retained with lower power consumption because the amount of airflow was reduced greatly by this modification.

After 194 days (point "f" in Fig. 6) the cold room was reconfigured into equally-partitioned rooms by installing a 50 mm-thick insulation panel. Prior to the construction of the partition, the temperature settings of the air conditioners had been changed to 30ºC on the 174th day (point "e" in Fig. 6) to maintain a temperature of 5ºC in the cold room during the construction of the partition. Power of the air conditioners increased then to 1.00 kW (point “e” in Fig. 7). Moreover, alterations were made so that the temperature of the cold room controlled the running of the ventilators in the warm room, cutting-in when temperatures increased over 5ºC. Fig. 9 shows a schematic diagram of the remodeled facility in the tunnel. For the rest of this paper, we refer to the new room as the cool room. After remodeling, cold-room temperatures fell rapidly to less than 3ºC, after which, on the 207th day (point “g” in Fig. 6), the temperature settings of the air conditioners were changed to 28ºC. As a result, the cold-room temperature was able to be kept at 5ºC accompanied by a reduction in power of the air conditioners to less than 0.80 kW (point “g” in Fig. 7). In contrast, cool-room temperatures stabilized between 12ºC and 13ºC, suitable for aging cheeses, meats, wines, and other such foods. This result indicates that by using insulation panels for partitioning a flexible facility of several rooms can be constructed in a tunnel, each room having a set temperature environment.

From around the 260th day after the commencement of the study, temperatures in the cold room increased gradually as midsummer was approaching. Again, temperature settings of the air conditioners were reset to 29ºC after the 325th day to maintain temperatures in the cold room at 5ºC.

After 1 year, the temperature of the cold room could be reliably maintained between 5ºC and 6ºC while power was kept at 0.80 kW. In addition, the temperatures of the warm room, mild room, and cool room could be maintained at 32ºC, 21ºC, and 13ºC respectively. Both the temperature and power consumption of each room were little affected by the increase in outside temperatures during summer.

*3.2 Relative humidity change of each room*

Fig. 10 shows the change in relative humidity for each room over a full year of operation. Humidity changes in the entrance space represent the original humidity changes in the tunnel prior to the installation. The humidity in each room was adjusted in an operation described below; however, it must be noted that the original humidity in the tunnel was over 99%.

Humidity in the warm room fell rapidly on commencement of operation and stabilized between 35% and 40% over the next 55 days. Concurrently, humidity in the cold room also fell rapidly and settled between 85% and 87% after 20 days. When the air came in contact with the heat exchangers in the outdoor units, some of that air became condensed at the surface of the heat exchangers and moisture drained from the units. The amount drained was higher while the humidity in the cold room was lowered (data not shown). Humidity in the mild room started to decrease rapidly after the ventilator was moved to the warm room from the cold room (point "b" in Fig. 10) but at the beginning had decreased gradually for a while.

The amount of lower-temperature air that flowed into the higher-temperature rooms through the side ditches became greater in expanding the ventilation capacity in the warm room. The lower-temperature air should contain a smaller amount of moisture; therefore, the humidity in the higher-temperature rooms, especially in the mild room, had decreased more rapidly after modification. In contrast, after one of the ventilators in the warm room was modified to force air from the entrance space (point "d" in Fig. 10), humidity in both the mild and warm room increased because the amount of air flow from lower-temperature rooms to higher-temperature rooms through the side ditches was reduced.

On the 134th day, 400 kg of bamboo chips that had been dried for 10 days in the warm room were laid over the ground of the mild room (point "c" in Fig. 10). The average size of each bamboo chip was less than 10 mm square and 5 mm thick. The moisture content in these bamboo chips was approximately 21.3%. Humidity in the mild room decreased to 80% after this treatment, whereas beforehand it was stable at 85%. Bamboo chips are seen as a low-cost material that can be used in humidity control in this facility. Moreover, it was found to be quite effective in controlling humidity in this facility by preventing evaporation of moisture from the soil surface.

Humidity in the remodeled cold room was lower after the original cold room had been partitioned into two rooms (point "f" in Fig. 10) because the amount of drainage from the outdoor units was increased by the decrease in temperature. In contrast, humidity in the cool room without a drainage system rose after modification because moisture started evaporating from the soil surface and wall surface.

Japan in summer is quite humid so the air in the entrance space was also humid. Therefore, an increase in humidity in the warm room, where a ventilator had been used to force humid air in, was observed over the summer season, as shown between days 200 and 350 in Fig. 10.

After the 285th day (point "h" in Fig. 10), a ventilator was installed in the insulation panel between the cool room and the innermost space to lower the humidity in the cool room; it started decreasing gradually after the modification and finally stabilized at 89%. After 395 days (point "i" in Fig. 10), the ground in the cool room was covered with a polyethylene sheet to prevent evaporation from the bare soil surface. The covering helped in reducing rapidly the humidity in the cool room to less than 80%, suitable again for many kinds of aged foods. As was previously mentioned, preventing evaporation from the bare soil surface is the most important means in controlling humidity in this facility. Incidentally, humidity in the cold room also decreased to less than 80% in conjunction with the decrease in humidity in the cool room.

*3.3 Computational analysis of heat transfer in this facility*

*3.3.1 History matching of the room temperature variations*

Fig. 11 shows the comparisons of the observed and estimated temperature of the warm room and the cold room. The air temperature at the exhaust blocks of both rooms was plotted on the figure as the estimated temperature. The estimated temperature of both rooms was in good agreement with the observation. The observed temperature of the cold room decreased slower than the estimated temperature during the first 10 weeks because the operation conditions were modified several times during that time as described above. These results indicate the validity of the computational model used in this study.

*3.3.2 Prediction of the temperature distribution of the facility*

Fig. 12 shows the estimated I-J (K=7) temperature distribution maps of the facility after 0, 10, 100 and 400 days from the beginning of the operation. Internal temperature of the tunnel wall was also increased or decreased with the variations in temperature of the warm room or the cold room respectively. One-meter-internal temperature of the tunnel wall in the cold room was estimated to be decreased to less than 10ºC after 400 days elapsed. The heat insulation property of the tunnel wall had been reinforced by their own temperature change. The cost of operating the facility will be reduced by the tunnel wall whose heat insulation property was reinforced.

Fig. 13 shows the estimated heat transmission in the tunnel wall in the warm room and the cold room calculated from the equations (2) and (6) with the estimated temperature shown in Fig. 6. The heat transmission of both rooms was decreased immediately from 1,600 J/sec after starting the operation and became stable after 200 days. The mean heat transmission in the tunnel wall in the warm room and the cold room between 100 and 300 days after was 300 J/sec and 414 J/sec respectively.

*3.3.3 Estimation of overall heat transmission coefficient of the tunnel wall*

The mean heat flux of the tunnel wall in the warm room ($q_{WW}$ (W/m$^2$)) and the cold room ($q_{WC}$ (W/m$^2$)) can be calculated by dividing the mean heat transmission by the surface area of the tunnel wall in each room. The mean heat flux of the tunnel wall was estimated at 2.08 W/m$^2$ for the warm room and 2.88 W/m$^2$ for the cold room respectively. Overall heat transmission coefficient of the tunnel wall in the warm room ($K_{WW}$ (W/m$^2$·K)) and the cold room ($K_{WC}$ (W/m$^2$·K)) can be calculated from following equations:

$$K_{WW} = q_{WW} / (T_W - T_0) \quad (10)$$

$$K_{WC} = q_{WC} / (T_0 - T_C) \quad (11)$$

where $T_0$ (K) is the original internal temperature of the tunnel wall. Although the original internal temperature of the tunnel wall was not measured, it was assumed to be same as the original atmospheric temperature in the tunnel, which had been measured before the experiments.

The mean temperature of the warm room was 304.6 K and the difference in temperature between the warm room and the original internal tunnel wall was 14.1 K. The mean temperature of the cold room was 278.7 K and the difference in temperature between the cold room and the original internal tunnel wall was 11.8 K. The overall heat transmission coefficients of the tunnel wall in the warm room and the cold room were estimated at 0.148 $W/m^2 \cdot K$ and 0.244 $W/m^2 \cdot K$, which were one fifth and one third of that of the insulation panel which has been installed in this facility, respectively. Namely, the heat insulation performance of the tunnel wall in the warm room and the cold room is similar to that of the insulation panel whose thickness is 250 mm and 150 mm respectively.

## 4. Discussion

### *4.1 Consideration of the suitable rated heating capacity of air conditioners*

Based on the heat balance of this facility described above, let us discuss the suitable rated heating capacity of air conditioners to construct a warm room and a cold room whose temperature is 31ºC and 5ºC respectively in this tunnel whose original temperature is 17.5ºC.

In the warm room, the heat quantity provided by the air conditioners and ventilation intake is equal to that discharged through the tunnel wall, the insulation panels and the ventilation exhaust; therefore, the heat quantity provided by the air conditioners ($Q_{ACpW}$ (W)) can be calculated from following equation:

$$Q_{ACpW} = Q_{WdW} + Q_{WdM} + Q_{WdIM} + Q_{VdW} - Q_{VpW} \quad (12)$$

$Q_{WdM}$ and $Q_{WdIM}$ are calculated from the equations (3) and (4) respectively. $Q_{WdW}$ can be calculated from the following equation using the overall heat transmission coefficients of the tunnel wall in the warm room described above.

$$Q_{WdW} = K_{WW} \cdot A_W \cdot (T_W - T_0) \qquad (13)$$

where $A_W$ ($m^2$) is the surface area of the tunnel wall. The difference between $Q_{VdW}$ and $Q_{VpW}$ are calculated from the following equations:

$$Q_{VdW} - Q_{VpW} = Q_V \cdot C_p \cdot \rho \cdot (T_W - T_0) \qquad (14)$$

where $Q_V$ ($m^3$/sec) is the ventilation rate which 0.022 $m^3$/sec was substituted for, $C_p$ (J/g·K) is the specific heat of air which 1.006 J/g·K was substituted for, and $\rho$ (g/$m^3$) is the air density which 1293 g/$m^3$ was substituted for.

In the cold room, the heat quantity discharged by the outdoor units is equal to that provided through the tunnel wall, the insulation panels and the water condensation; therefore, the heat quantity discharged by the outdoor units can be calculated from following equation:

$$Q_{ACdC} = Q_{WpC} + Q_{MpC} + Q_{EpC} + Q_{LpC} \qquad (15)$$

$Q_{MpC}$, $Q_{EpC}$ and $Q_{LpC}$ are calculated from the equations (7), (8) and (9) respectively. $Q_{WpC}$ can be calculated from the following equation using the overall heat transmission coefficients of the tunnel wall in the cold room described above.

$$Q_{WpC} = K_{WC} \cdot A_W \cdot (T_0 - T_C) \qquad (16)$$

$Q_{ACpW}$ and $Q_{ACdC}$ were estimated at 942 W and 702 W respectively by the calculation using above equations. The sum of $Q_{ACpW}$ and $Q_{ACdC}$ is the intermediate heating capacity of the air conditioners to keep the temperature of the warm room and the cold room at 31ºC and 5ºC respectively. According to this result, the air conditioners whose total rated heating capacity is more than 3.3 kW should be installed in this facility to construct such rooms.

The procedure of modeling the underground facility and estimating the overall heat transmission coefficients as described above could be a great help in the design of similar facilities in underground spaces.

*4.2 Energy efficiency of this facility*

Because there has been no report of energy performance of similar multi-purpose facility, let us consider the energy performance of this facility by comparing our cold room with other typical surface cold storages which have similar temperature. Temperature of our cold room had been finally stable at 5-6ºC while power had hovered around 0.80 kW. Assuming these values for the whole year, the annual power consumption reached 7008 kWh. The capacity of the cold room at that time was 60 $m^3$; therefore, the annual power consumption of the cold room per unit volume was 116.8 $kWh/m^3$/year. In Fig. 14, this value has been compared with that of other typical surface cold storages whose annual power consumption per unit volume were reported by the commercial refrigerator and showcase classification standards subcommittee, energy efficiency standards subcommittee, advisory committee for natural resources and energy, ministry of economy, trade and industry of Japan (2011) and Yanagisawa (2003). Although the capacity of other cold storages was different from that of this cold room, according to the trend line connecting the points of other cold storages, it can be assumed that the annual power consumption per unit volume of a typical cold storage whose capacity was similar to this cold room was 500 $kWh/m^3$/year. Accordingly, energy efficiency of this facility is 4 times higher than that of typical cold storage. Moreover, our facility has the benefit that it can be utilized for various food and drink preparation purposes because several rooms can be operated at different temperatures at the same time. Although similar facility will require not only installing the inner equipment but also improving infrastructure such as roads, water and sewerage, electricity, and so on, the initial costs are expected to be lower than for surface facilities because of its low costs for land and construction materials; therefore, it is evident from this study that our system is economically feasible and environmentally friendly.

*4.3 Operational problems in actual use*

The raw materials and processed products will be often brought into and taken out of the rooms in actual use of this facility. We worked in this facility every 5-10 days during the experiment, which caused small fluctuations and increment of the power consumption as found in Fig. 7. Several workmen entered and exited the rooms frequently and worked in the facility during the construction of the later partition, which increased power consumption to average 1.02 kW from 0.82 kW to keep the temperature of the cold room at 5ºC as found between points of “e” and “f” in Fig. 7. The power consumption will be increased by 25% approximately to keep the constant temperature of the rooms by the works in this facility in actual operation.

**5. Conclusion**

The aim of this pilot study was to construct several different temperature rooms, which could be used for the aging, brewing and fermentation of various foods and drinks, in a disused tunnel of an uncompleted rail line by erecting insulation partitions and room air conditioners. Indoor and outdoor air conditioning units commercially sold for home use were installed in the first and third rooms from the entrance of the tunnel, with air conditioners running in heating mode during testing. Temperature and humidity for each room and power consumption of the air conditioners were monitored continuously and the potential and advantage of utilizing the tunnel on this system were estimated. The following conclusions were obtained.

1) After 1 year of continuous operation, four different temperature regimes: cold (5ºC), cool (13ºC), mild (21ºC), and warm (32ºC) were maintained in separate rooms with the power consumption of 0.80 kW.

2) Both the temperature of each room and power consumption of the air conditioners were little affected by seasonal variations including humidity and summer temperatures.

3) Relative humidity in the cold room was kept between 75% and 85%, suitable for fermentation and aging of many kinds of foods. Preventing the evaporation from the bare soil surface was demonstrated to be the most important means in controlling the humidity in this facility.

4) The computational model constructed in this study was able to simulate the experimental temperature variations of the warm room and the cold room respectively, indicating the validity of

the computational model.

5) Internal temperature of the tunnel wall was increased or decreased with the variations in temperature of the warm room or the cold room respectively with the operation time. The heat insulation property of the tunnel wall had been reinforced by their own temperature change. The tunnel wall whose heat insulation property was reinforced will be helpful for reducing the cost of operating the facility.

6) We demonstrated the procedure to estimate the overall heat transmission coefficients of the tunnel wall which was a great help in the design of similar facilities in underground spaces.

7) This facility demonstrated low energy consumption compared with typical surface facilities. Energy performance will improve if this facility is utilized for several processes such as the aging, brewing and fermentation at a same time.

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Captions for table and figures

Table 1 Thermophysical properties of each material

Fig. 1. Location map of Hatogawa tunnel in Karatsu, Saga, Japan.

Fig. 2. Schematic diagram of the temperature-controlled of the underground facility.

Fig. 3. Photographs of each of the rooms of the underground facility.

Fig. 4. Schematic diagram of the computational model of the facility.

Fig. 5. Schematic diagram of the heat transfer in this facility.

Fig. 6. Variations in room temperature and outer temperature over the testing period.

Fig. 7. Variation in power consumption of the air conditioners during the test period.

Fig. 8. Thermal image of the surface temperature distribution in the cold room.

Fig. 9. Schematic diagram of the remodeled facility.

Fig. 10. Variations in relative humidities of the rooms over the testing period.

Fig. 11. Comparisons of the measured and the estimated temperatures in the warm room and the cold room.

Fig. 12. Temperature distributions of the facility estimated by the computational analysis.

Fig. 13. Heat transmissions from the tunnel wall in the warm room and the cold room estimated by the computational analysis.

Fig. 14. Comparisons of annual power consumption per unit volume between this facility and other facilities.