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VENTILATION ANALYSIS OF UNDERGROUND HYDROELECTRIC POWER STATIONS

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SUMMARY

Since thermal environment in the power house of hydroelectric power station is influenced by fluctuation of outdoor air, radiation of heat and moisture from rock surface and heat strage of surrounding bedrock, it is difficult to design the ventilation and air–conditioning system adequately.

Then Long–term field measurements were taken to gain a precise measure for the ventilation design of the power house. Futhermore, a ventilation program which is in consideration of above conditions was developed for the aim of producing design guidance for the power house.

Based on observed results, a simulation was performed for the power station from which observations had been taken. The trends in temperature and humidity at each point have been accurately followed, and good agreement with observations was achieved.

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INTRODUCTION

Recently, almost all large scale hydroelectric power stations built in Japan have been of the pumped–strage type. In this type, the power house is constructed in a cavern with a volume of tens of thousand cubic metres excavated within mountain bedrock.

Generally, the humidity in the power house is high, hence in order to protect electrical equipments, the prediction of humidity level becomes a vital part of ventilation design. However, in conventional ventilation design for power stations, the main aim has been the removal of heat generated by equipments, and there has been hardly any consideration of humidity. In addition, various problems have occured due to the effects on the humidity level from such factors as changes in external climate, heat storage in bedrock and heat or moisture release from the rock surface.

This paper presents the result of measurements taken of present condition in an existing underground power station and that of a predictive analysis to use the simulation program with consideration of the non–linear thermal propaties.

OUTLINE OF VENTILATION SYSTEM AND CURRENT PROBLEM AREAS

The general arrangement of an underground hydroelectric power station together with ventilation facilities are shown in figures

1 and 2 respectively.

The access tunnel, which has a length of several hundred metres, serves not only as a route for introduction and removal of equipments, but also as a vent for the supply of outside air. Air introduced via the access tunnel passes through air conditioning equipments (cooling, de–humidity, re–heating) located at the tunnel end, and is then fed to each floor of the power house.

However, being located underground, the design for ventilation in the power house are very severe. The most important problem is the humidity level. In underground structures, the temperature of the surrounding rock remains constant throughout the year. In summer, the air from outside is cooled by the rock surface, causing condensation and increasing the level of relative humidity. Futhermore, there is seepage of spring water from the surrounding rock, again increasing humidity, and having a worrying influence on equipments in the power house. In addition, with regard to the temperature in the power house, since heat is absorbed and released by the rock, heat storage effect is involved, and must be adequately taken into account in ventilation design.

LONG–TERM OBSERVATIONS OF AN UNDERGROUND HYDROELECTRIC POWER STATION

In order to gain a precise measure of the problem areas relating to ventilation design for the underground power station, a program of long–term observations were carried out over one summer and one winter.

(1) Observation Method

Measurements were taken over a summer and winter period; July – August 1988 and February – March 1989. All measurements were taken at the " M" power station. An outline specification for the power station is given in table 1 . It was known from previous survey that this power station suffered from relatively high seepage.

The measurement items are shown in table 2 . Various sensors and recording devices were installed throughout the measurement period, and representative measurements of the thermal environment were taken at 15 minutes intervals.

(2) Results of observations

(a) Temperature and humidity levels

Table 3 shows results for the monthly average values of temperature and humidity, together with the daily range of change. Looking firstly at the situation within the access tunnel, the air flow was cooled by the rock surface in summer, so that at the end of the tunnel the relative humidity reached about 100% and condensed on the wall surface. In winter, seepage occured along the bottom surface of the tunnel, causing a large increase in the absolute humidity of the air flow. At the end of the tunnel, absolute increses in humidity of 1.8 g/kg' were recorded. Additionally, the variation in temperature at the tunnel end was only found to be about 0.5 degrees. This stability in temperature indicated the heat absorption effect of the surrounding rock. It was clear that this effect would have to be included when carrying out any sumulation.

Within the power house itself, increase in humidity were observed during the summer period for locations of basement level and below, but because of de–humidifying and re–heating action by air conditioning equipments, and generation of heat by equipment, the relative humidity was about 60%. There were also increase of absolute humidity in the winter period at each floor, but in this case the relative humidity was between 30 and 70%.

(b) Material characteristics

From the observed data, calculations were made to evaluate the surface conductance of the rock, the generated heat value by equipments for each floor, and the coefficient of moisture transfer. These results are shown in table 4 .

The surface conductance was established by using the gradient of relationship between changes in the heat energy flow, and the difference in representative temperature of air and surface (Figure 3). From this process, the generated heat value by equipments for each floor was also evaluated using the steps in the y coordinate. The values obtained for surface conductance were as follows : access tunnel 3.01(Kcal/m^2 · h ·°C), within the power house 3.01(Kcal/m^2 · h·°C) for B1–B3 which are isolated from the surrounding rock by a cavity wall, and 6.45(Kcal/m^2 · h·°C) and 7.74(Kcal/m^2 · h·°C) for B4 and B5 floors where there is a simple concrete wall in place of the cavity wall.

The generated heat value was compeared with quantities of caluculated from actual machine specification and the net working rate of the power station. For all floors, the observed heat value was only 30 – 40 % of the calculated value. It is thought that the remainder was absorved directly from the basements of the equipments, or carried away in seepage water. This result suggests that it is likely to over–estimate the amount of generated heat value in design. Although this may lead to a safe design from the temparature viewpoint, it could on the other hand cause an under–estimate of the level of relative humidity, resulting in an unsafe design overall.

The coefficient of moisture transfer was evaluated from the change of moisture content in the air flow, and the difference in water vapour density saturated at the wall surface temperature and the water vapour density of the flow (Figure 4). In the access tunnel, the values obtained were 1.75×10^{-3} (m/s) for the summer period (with condensation), and 5.30×10^{-4} (m/s) for the winter period (with humidifying), indicating a strong seasonal dependence. For the power house, values were between 4.00×10^{-4} – 3.00×10^{-3} (m/s) varying both with season and floor level.

(C) Heat balance

In order to gain an understanding of the heat balance among the tunnel, air conditioning equipmnts and house interior, a quantitative evaluation of the heat transfer was made from the changes of entropy in the flowing air. This heat transfer is shown in figures 5 and 6 for the summer (July) and winter (February) periods.

For " M" power station in the summer period, the removal of latent heat load produced by ventilation and bedrock, occured not only through heat absorption by the tunnel wall, but also by the work of the de–humidifying equipment in large part. However, the sensible heat load from the re–heater included in the de–humidifier was increased. In the winter period, a balance was maintained between the radiated heat from the tunnel rock and generated heat within the power house, and heat lost through ventilation and absorption by surrounding rock. Moisture produced by the power house surface rock made up the larger part of the latent heat load, comprising 60% of the total.

DEVELOPMENT OF A VENTILATION SIMULATION PROGRAM

For the aim of producing a design guidance for the underground power station construction or the projects to improve the thermal environment of existing facilities, a ventilation simulation program was developed which would allow predictions of same accuracy to be made in advance. The program was assembled on a personal computer, and employed a greatly simplified model to enable the results to be obtained rapidly. It can be easily operated by the designer.

(1) Modeling

Figure 7 shows the model used for the simulation of the power station. The model is divided into the elements representing the access tunnel, air conditioning equipment, and the each floor of the power house. For each part, basic equations were assembled describing heat transfer, water vapour and material transfer properties, and predictive calculations were made for temperature and humidity using differential methods.

In order to simplify the model as far as possible, the access tunnel was taken as a cylindrical coordinate and divided into elements along its axis (figure 8). For the power house, one element was used for each floor, with the top and bottom floors being half–spheres, and intermediate floors being circular in form. It was assumed that there was no heat exchange between floors. Material characteristics were used to the observation results descrived above.

In this way, it was possible to formulate a ventilation model of the power station which allowed a one–dimensional solution of the heat flow.

(2) Equations for analysis

The basic equations used in the temperature/humidity prediction simulation are shown below.

(tunnel elements)

tunnel interior atmospheric heat balance

$$A \cdot Ca \cdot \gamma a \cdot \left(\frac{d\theta a}{dt} + Ua\frac{d\theta a}{dx}\right) = S \cdot \alpha \cdot (\theta s - \theta a)$$

tunnel interior water vapour mass balance

$$A \cdot \left(\frac{dXa}{dt} + Ua\frac{dXa}{dx}\right) = S \cdot \beta \cdot (Xs - Xa)$$

tunnel wall surface heat balance tunnel

$$-\lambda c \cdot \left(\frac{d\theta c}{dr}\right)_{r=rs} = \alpha \cdot (\theta s - \theta a) + He \cdot \beta \cdot (fs - fa)$$

surrounding rock heat ba lance

$$Cc \cdot \gamma c\frac{d\theta c}{dt} = \lambda c \cdot \left(\frac{d^2\theta c}{dr^2} + \frac{1}{r} \cdot \frac{d\theta c}{dr}\right)$$

(power house elements)

power house interior atmospheric heat balance

$$Va \cdot Ca \cdot \gamma a\frac{d\theta a}{dt} = F \cdot \alpha \cdot (\theta s - \theta a) + Ca \cdot \gamma a \cdot \sum_{i=1}^{n}\{Wi \cdot (\theta ai - \theta a)\} + Q$$

power hall interio rwater vapour mass balance

$$Va\frac{dXa}{dt} = F \cdot \beta \cdot (Xs - Xa) + \sum_{i=1}^{n}\{Wi \cdot (Xai - Xa)\}$$

power house wall surface heat balance

$$-\lambda c \cdot \left(\frac{d\theta c}{dy}\right)_{y=ys} = \alpha \cdot (\theta s - \theta a) + He \cdot \beta \cdot (fs - fa)$$

power house surrounding rock heat balance

$$Cc \cdot \gamma c\frac{d\theta c}{dt} = \lambda c\frac{d^2\theta c}{dy^2}$$

Where,

A	:Section area of tunnel element	(m^2)
x	:Element length along tunnel axis	(m)
C	:Specific heat of air	(Kcal/Kg·℃)
y'	:Depth from bedrock	(m)
F	:Surface area of power house wall	(m^2)
α	:Surface conductance	(Kcal/m^2·℃·h)
He	:Latent heat rate	(Kcal/Kg)
β	:Coefficient of moisture transfer	(m/h)
Q	:Generated heat value	(Kcal/h)
γ	:Specific gravity	(Kg/m^3)
S	:Circumference of tunnel	(m)
θ	:Temperature	(℃)
U	:Air velocity	(m/h)
λ	:Thermal conductivity	(Kcal/m·℃·h)
V	:Volume of power house	(m^3)
W	:Air change rate	(m^3/h)
X	:Absolute humidity	(Kg/Kg')
f	:Moisture content rate	(Kg/m^3)
r	:Radius	(m)
t	:Time	(h)

Note:

a :Air
c :Concrete or bedrock
i :Inflow rate
o :Outflow rate
s :Wall

(3) Design conditions

A simulation was performed for the power station " M" from which observations had been taken. Values such as the length and area of the tunnel, and structural conditions, were calculated from the drawings. The ventilation flow rate and surface conductance were taken as the values obtained from the observations. A value for the rock density was taken from reference.

(4) Results of the simulation

The calculation results of temperature and humidity are shown in figures 9 and 10. The results are taken as values obtained after a running period of 24 days, a time span thought sufficient to achieve steady–state conditions.

The errors between observed and calculated values are a maximum of 2.2 °C for temperature and 1.6g/kg' for absolute humidity. However, taking the power station as a whole, the trends in temperature and humidity environment at each point have been accurately followed, and good agreement with observations was achieved.

CONCLUDING REMARKS

An investigation was carried out into conditions of an existing power station, and an understanding of the thermal power station, and an understanding of the thermal environment was gained. Results from the investigation enabled the physical data necessary for an ventilation simulation to be evaluated. A significant difference was shown in relation to the use or non–use of a cavity wall, and a study is now in progress into the possible adaption of future power stations in the light of these results.

Heat generated from equipment within the power hall only amounted to about 30% of the value calculated from consideration of the net working rate of the equipments. It is thought that this is due to heat being transmitted directly to the rock, or being absorbed and carried away by seepage water. This effect needs to be considered in the design process.

An air conditioning simulation program for underground hydroelectric power stations, which takes into account both sensible and latent heat, was developed. Using this program, a simulation was performed for the existing power station on which observations had been made. Relatively good agreement was obtained between observed and calculated values, confirming the effectiveness of this method.

It is planned to employ this program in the future on the planning of air conditioning for new power stations now under design.

LITERATURE

[1] The Japan Society of Mechanical Engineers, " JSME Data Book: Heat Transfer 4th Edition" , The Japan Society of Mechanical Engineers, Japan, (1986)

[2] U.Inoue, " Handbook of Heating and Air–Conditioning 3rd Edition" , Maruzen Inc., Japan, (1985)

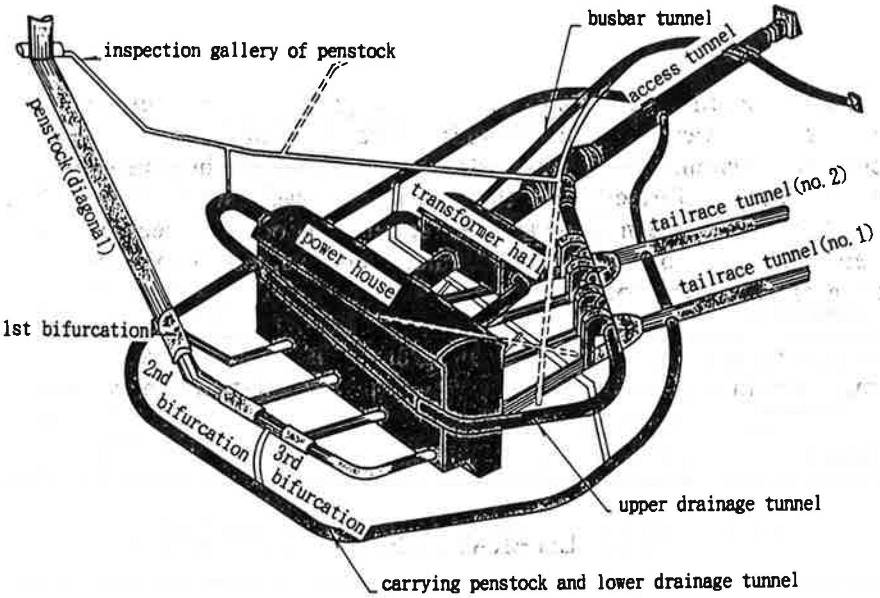

Figure-1 Plan of power house

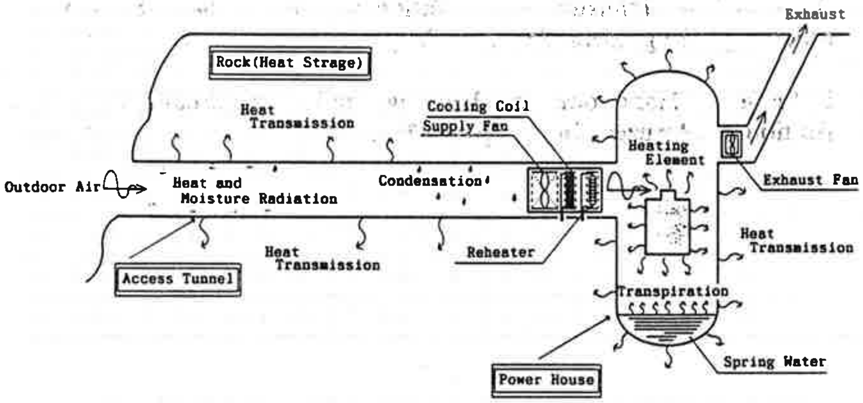

Figure-2 Ventilation mechanism of power house

Table-1 Outline specification for the power station

Generating Capacity		288,000 (kW)
Access Tunnel	Length	458 (m)
	Section Area	23.6 (m^2)
Power House	Scale	5 stories below
	Volume	31,900 (m^3/h)
Air Change Rate		35,000 (m^3/h)

Table-2 Measurements items

		Access Tunnel					Air Conditioner	Power House				
		0 m	50 m	125 m	250 m	450 m		1 F	2 F	3 F	4 F	5 F
Air	Temperatuere	○	○	○	○	○	○	○	○	○	○	○
	Relative Humidity	○	○	○	○	○	○	○	○	○	○	○
Wall Temperature		╱	○	○	○	○ ╱	○	○	○	○	○	○
Air Velocity		○	–	–	–	○	○	○	○	○	○	○

Table-3 Results for the monthly average varue of temperature and humidity

		Temperature (℃)		Absolute Humidity (g/Kg')	
		July	February	July	February
Access Tunnel	Inlet	21. 9±2. 7	4. 3±4. 0	13. 0±1. 1	1. 9±0. 9
	Outlet	18. 1±0. 5	8. 4±0. 7	11. 6±0. 4	3. 7±0. 7
Air Conditioner		23. 8±1. 7	12. 0±0. 6	9. 7±0. 4	3. 9±0. 6
Power House	1 F	24. 2±0. 6	16. 8±1. 4	9. 2±0. 2	3. 7±0. 7
	2 F	24. 3±0. 4	15. 7±0. 5	10. 0±0. 2	6. 2±0. 6
	3 F	22. 6±0. 4	16. 2±0. 7	11. 0±0. 3	5. 8±0. 6
	4 F	21. 2±0. 3	15. 4±0. 4	9. 9±0. 2	5. 2±0. 5
	5 F	19. 4±0. 5	14. 1±0. 1	10. 1±0. 3	7. 0±0. 4

Table-4 Results of material characteristics

		Surface Conductance (Kcal /m^2 ·℃·h)	Generated Heat Value (Kcal/h)	Coefficient of Moisture Transfer (x10 $^{-3}$)	
				July	February
Access Tunnel		3. 01	0	1. 75	0. 53
Power House	1F	3. 35	13840	0	0
	2F	2. 58	6360	0. 21	0. 39
	3F	3. 35	5250	0. 54	0. 40
	4F	6. 45	2410	0. 16	0. 96
	5F	7. 74	0	0. 29	2. 96

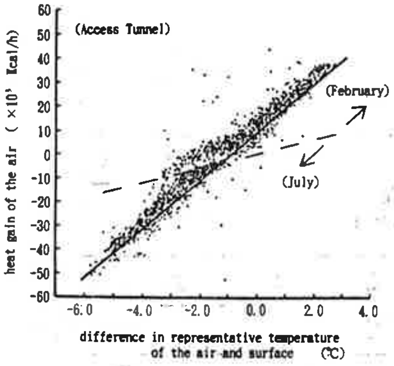

Figure-3 Surface conductance

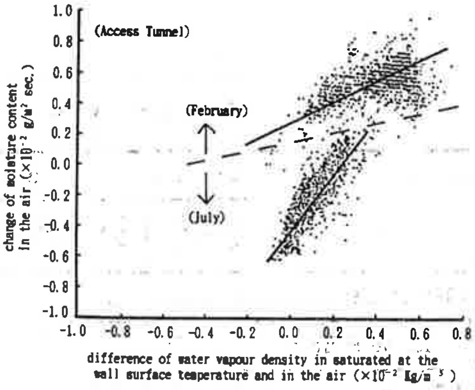

Figure-4 Coefficient of moisture transfer

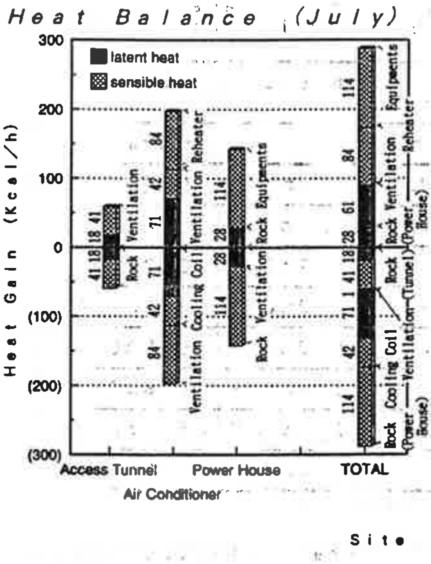

Figure-5 Heat balance (July)

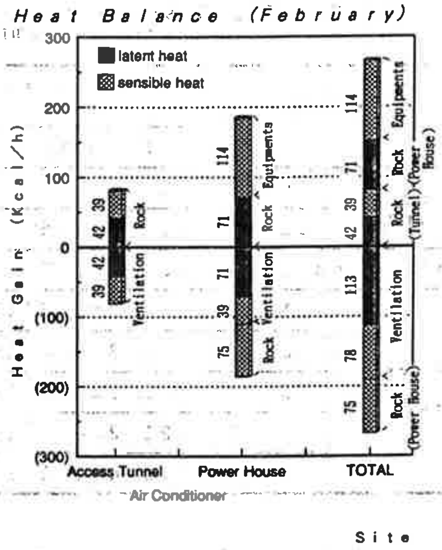

Figure-6 Heat balance (February)

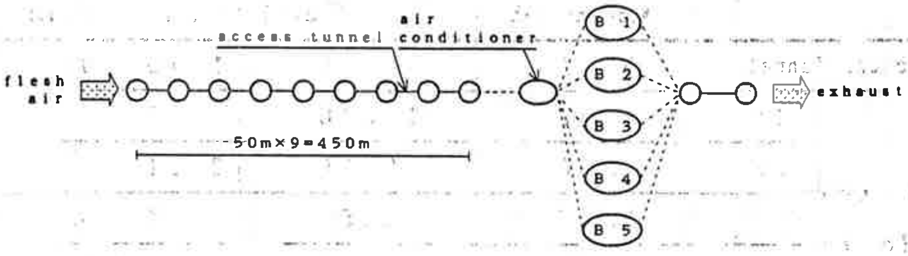

Figure-7 Simulation model of the power station

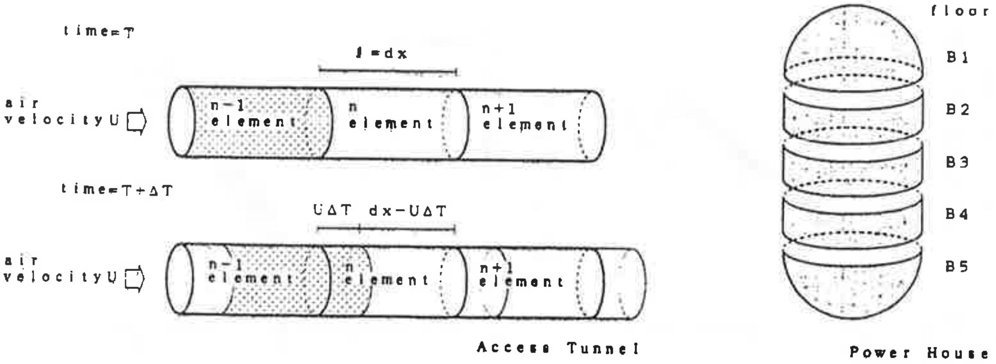

Figure-8 Elements of access tunnel and power house

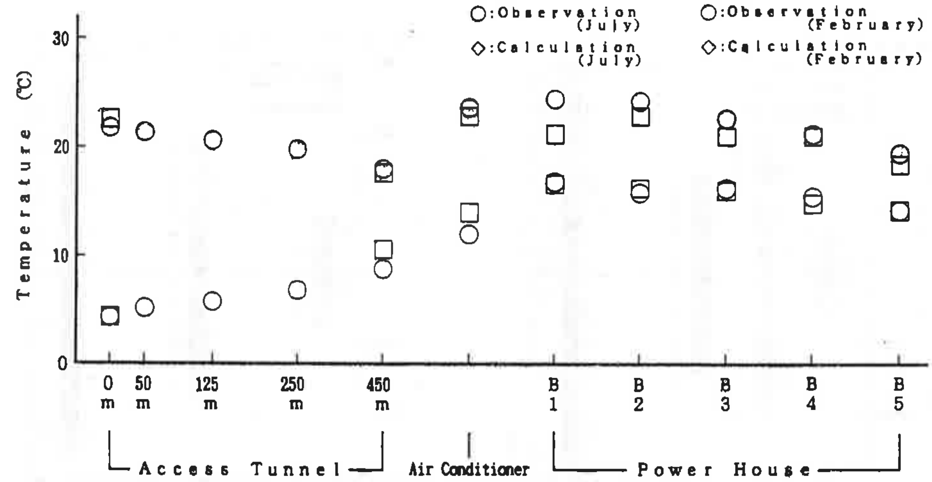

Figure-9 Simulation results (temperature)

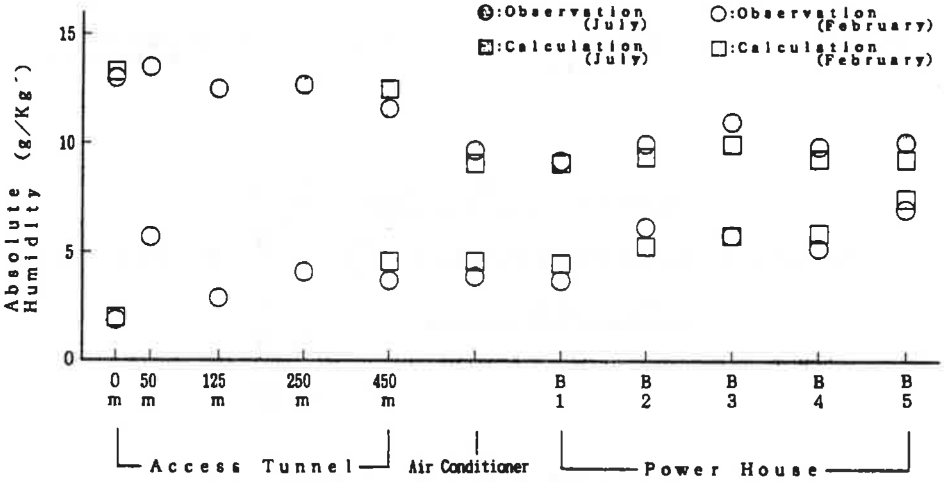

Figure-10 Simulation results (absolute humidity)