

VENTILATION PERFORMANCE OF SOLAR CHIMNEY WITH BUILT-IN LATENT HEAT STORAGE

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1. INTRODUCTION

Solar-induced ventilation could be provided by incorporating the solar chimney with buildings. This technique is getting popular in new constructions which are intended to exploit renewable resources to save conventional energy without sacrificing indoor thermal comfort and air quality. Authors [1] [2] have been conducted various experimental and theoretical studies on ventilation performance of solar chimney. The experimental parameters are heat generation rate, size of chimney gaps and inclination of chimney. The new calculation model for predicting the air flow rate was proposed and the calculated results are in good agreement with the experimental ones. These studies air aimed at the solar chimney ventilation during the daytime, but the ventilation also during the nighttime is also desired if possible. Authors focus on following problems about the solar chimney ;

(1) A solar chimney is not able to work for natural ventilation during the nighttime.

(2) As fluctuation of solar radiation during the daytime changes air flow rate, a solar chimney is an unstable system.

The idea to solve these problems is the usage of the latent heat. The latent heat stored in daytime is available for the nighttime ventilation by a solar chimney. No work has been performed on a solar chimney with built-in latent heat storage for evening / night ventilation. A solar chimney with built-in latent heat storage for prolongation of the natural ventilation operation was tried to develop. This paper presents the description of the prototype solar chimney with PCM (Phase Change Material) storage. A numerical model for predicting air flow rate in a solar chimney and temperature of aluminum (Al) plate, air and PCM are introduced as well.

2. FABRICATION AND DESCRIPTION OF THE PROTOTYPE SOLAR CHIMNEY

A solar chimney with built in LHS (= Latent Heat Storage) module was fabricated. The prototype was fabricated and installed on the roof of eight-story building in the site of Department of Architectural Engineering, Osaka University for testing thermal performance. A cross-sectional view and photograph of the prototype solar chimney using PCM for latent heat storage are shown in Fig.1 and Fig.2. An innovative idea has been applied to design an absorber of the present prototype solar chimney. This absorber consists of an aluminum (Al) plate with built in PCM. Sodium Sulfate Decahydrate " $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$ " originally made for the floor heating was used as PCM for latent heat storage and was encapsulated in the rectangular container with the dimensions of 0.6m length \times 0.25m width \times 0.025m thickness. Six encapsulated PCM modules were packed behind the black coated absorbing aluminum (Al) plate whose emissivity is 0.94. The total mass of the PCM is about 23.16kg. The specifications of the prototype set-up and thermo-physical properties of the PCM are given in Table 1. The transmitted solar radiation through the glass cover is partly absorbed by rectangular encapsulated PCM modules and stored in the PCM, as latent heat thermal energy, and partly transferred to the air flowing over the absorber surface. When solar energy is collected and transferred to the PCM, its temperature is raised from the initial temperature to the higher temperature over melting point. Hence, the temperature of the air inside the chimney also increases and reaches its maximum at the collector outlet. The air density gradient between the inside and outside the chimney increases a natural upward flow of air in the chimney.

Ventilation and heat storage in PCM occur during daytime simultaneously, while evening / night ventilation is induced mainly by discharge of the latent heat stored in PCM. PCM transfers stored heat to air flowing over the aluminum (Al) plate. This stored heat is used to generate the temperature difference in the evening or when there is no sun irradiation. The thermally induced flow depends on the level of solar radiation, weather conditions, geometry and orientation of system and the PCM's storage properties. The prototype of chimney was oriented to face south and tilted 45 degree with respect to the horizontal. This chimney was fabricated and installed on the roof of an eight-story building in Osaka, Japan to test the ventilation performance of a solar chimney. Seventy-seven 'T' type calibrated thermocouples, with the accuracy of ± 0.2 degree C, were used to measure the temperatures of the various elements of the chimney. These points were located on/in the absorbing (Al) plate, inside the PCM, surface of the PCM modules, air inside the chimney, outer surface of the glazing, top and bottom of the insulation, inside the glass wool insulation, ambient air and so on. A part of the positions of thermocouples are shown in Fig.3. A pyranometer was used to measure solar irradiance at inclined surface with the accuracy of 1.5%. Another pyranometer was used to measure the solar irradiance on a horizontal surface with the accuracy of 2.5%. All data were recorded at intervals of 10s.

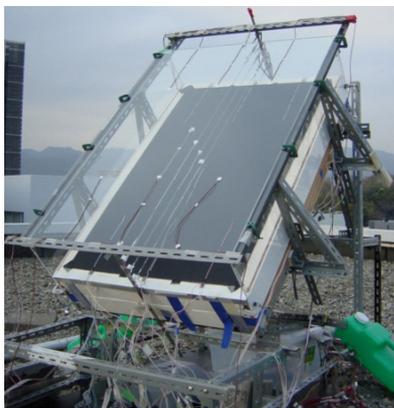


Fig.1: A photograph of the prototype solar chimney with built-in PCM modules for natural ventilation

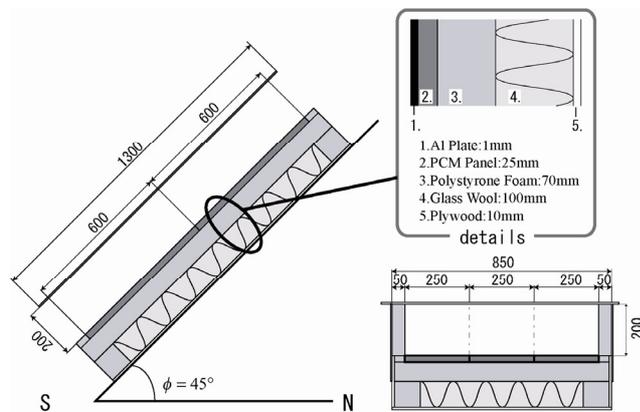


Fig.2: Cross-sectional view of chimney with built-in PCM storage

Table 1: Specification of the prototype solar chimney and thermo physical properties of PCM

Cover System		
Material		Glass
Dimension		1400 mm × 900 mm × 600 mm
Absorber		
Plate		Aluminum
Thickness		1 mm
Surface coating		$\alpha = 0.94$ ($\alpha = \text{emissivity}$)
Latent Heat Storage Material		
Phase Change Material (PCM)		$\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$
Melting Point		32 degree C
Freezing Point		30 degree C
Latent Heat of Fusion		126 kJ/kg
Density		
	Solid	1390 kg/m ³
	Liquid	1410 kg/m ³
Thermal Conductivity		
	Solid	0.19 W/m K
	Liquid	0.22 W/m K
Specific Heat		
	Solid	3.6 kJ/kg K
	Liquid	3.5 kJ/kg K
Gap		
Absorbing plate to cover glass		200 mm
Inclination Angle		45 degree
Insulation		
Polystyrene		70 mm
Glass wool		100 mm

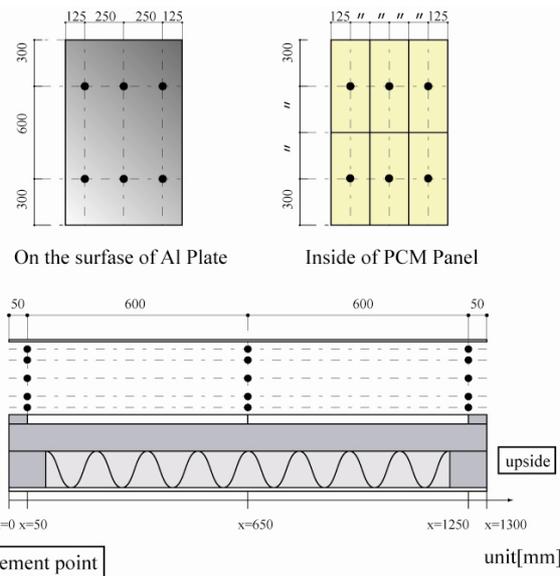


Fig.3: The positions of thermocouple inside the solar chimney

3. THERMAL BEHAVIOR IN SOLAR CHIMNEY WITH BUILT-IN LATENT HEAT STORAGE

Experiments have been conducted to get hold of thermal behavior in the solar chimney with built-in PCM. In this paper, two conditions have been discussed; (i) the part of PCM melted on 14-15 Feb. 2005. (ii) PCM hardly melted on 23-24 Jan. 2005. Variation of global solar radiation and wind velocity air are shown in Fig.4 and temperature variation of aluminum (Al) plate, PCM and ambient air are shown in Fig.5 and Fig.6. These figures also show the variation of temperatures on the top and bottom of the solar chimney. As shown in Fig.5 and 6, the collected solar energy transferred to the PCM via aluminum (Al) plate raises PCM temperature from the initial temperature to the higher temperature around the melting point. Initial change in temperature is a faster process because of the high heat transfer rate to the PCM. After this rapid increase over the melting point, the temperature becomes somewhat constant during the melting period. PCM partly melted on 14-15 Feb. 2005 (Fig.5) and it reached the maximum temperature (34.3 degree C) around 13:30 P.M. at the maximum solar radiation (906 W/m²) received on the collector. The maximum temperature difference between PCM and the ambient air was about 20 degree C and that between Al plate and ambient air was about 40 degree C respectively. From 17:00 P.M. to 21:00 P.M. in Fig.5 and 6, it was seen that the inclination of the temperature decay of PCM is more gradual than the other hours. Although this part is not between 30 degree C and 32 degree C, the effect of latent heat discharge is observed during this period. This latent heat discharge will enable the steady and long-term natural ventilation. On the other hand Fig.6 shows the results when PCM hardly melted on 23-24 Jan. 2005 with the maximum temperature and solar radiation of 12.4 degree C and 325 W/m² respectively. Above-mentioned latent heat discharge was not observed.

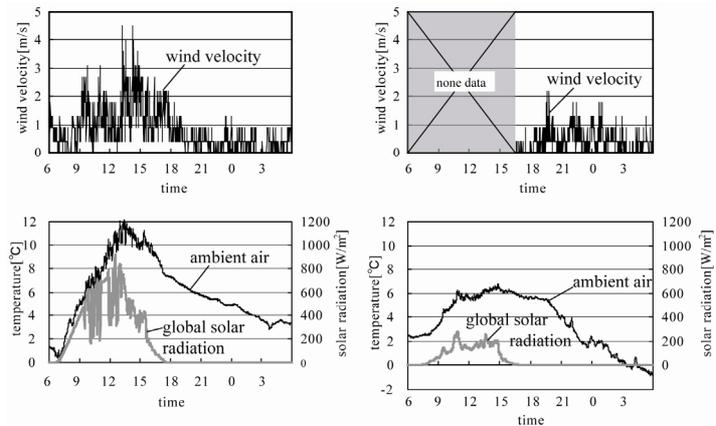


Fig.4: Variation of solar radiation, ambient air temperature and wind velocity on 23-24 Jan. and 14-15 Feb. 2005

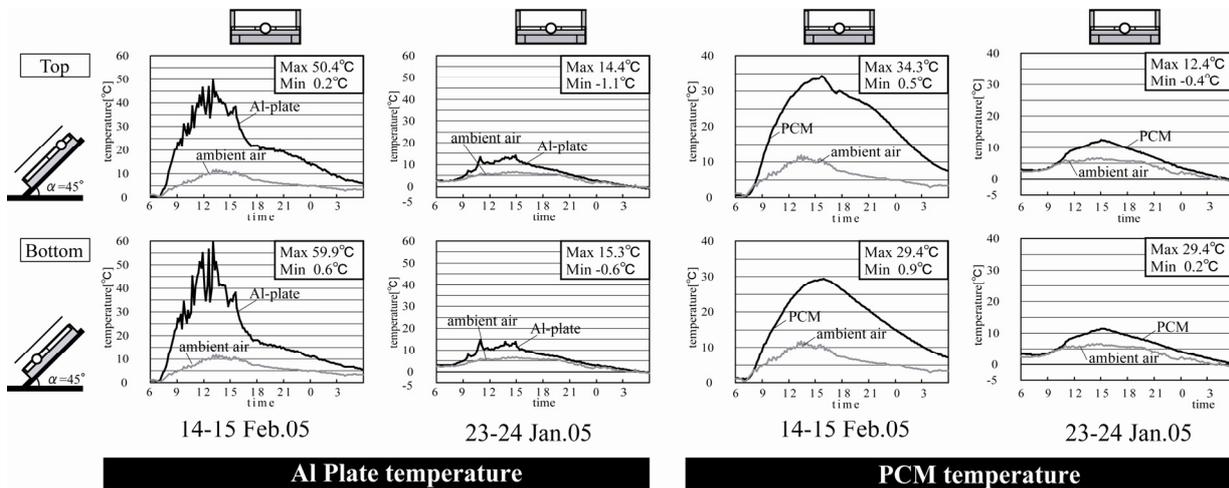


Fig.5: Temperature variation of the aluminum plate and ambient air on 23-24 Jan. and 14-15 Feb. 2005

Fig.6: Temperature variation of PCM and ambient air on 23-24 Jan. and 14-15 Feb. 2005

4. MEASUREMENT OF FLOW RATE IN THE PROTOTYPE SOLAR CHIMNEY

The prototype of the solar chimney was installed on the ground level to make measurement of flow rate in the prototype in consideration that the influence of the outside wind on the ground level is smaller than that on the roof

(see Fig.7). The airflow rate inside the solar chimney was measured by means of tracer gas technique. Fig.8 shows a measurement setup for the measurement of tracer gas concentration. SF₆ gas was emitted at the inlet of the chimney and the gas concentration was measured at the outlet of the chimney. The flow rate in the chimney is calculated by equation (1) shown in Fig.8 from the measured gas concentration. Tracer gas was generated from eight vinyl tubes installed in the inlet of the chimney and the concentration of tracer gas was measured at the inlet of the chimney by sixteen vinyl tubes connected to a gas monitor. The emission rate of tracer gas was 0.003m³/h. The measurement of concentration in the chimney was carried out for 30 minutes every 2 hours from 13th to 14th Feb. 2006. The tracer gas concentration in the chimney was measured by a fast-response gas monitor (INNOVA Type 1311). Outdoor temperature, wind velocity and solar radiation are shown in Fig.9-12. The solar radiation in Fig.9 is measured at inclined surface of the glazing. The wind velocity and direction were measured at three meters above ground level by a three dimensional anemometer.

The variation of the flow rate calculated from the measured concentration of tracer gas in the chimney is shown Fig.12. This value of flow rate consists of the flow rate caused by stack effect and outdoor wind force. It is seen that the flow rate is stable in daytime (from 10:00 to 14:00). Although the outside wind velocity in the nighttime is more stable than that in the daytime, the flow rate in the nighttime is varying. This seems to be caused by the problems in the measurement method of the gas concentration. For example, the following problems can be listed;

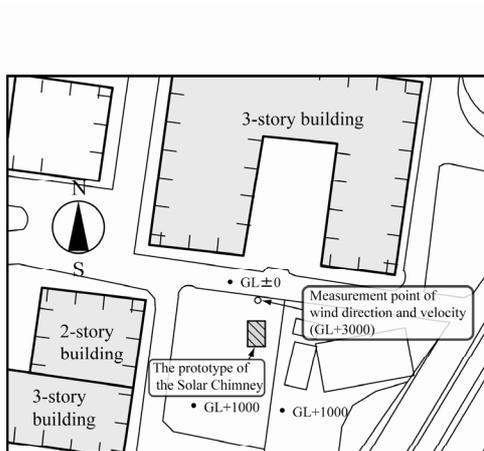


Fig.7: Site plan of the prototype solar chimney

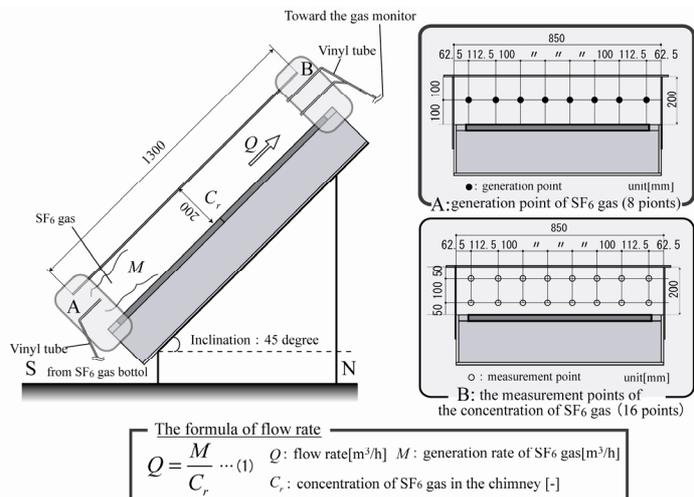


Fig.8: Outline of the concentration measurement

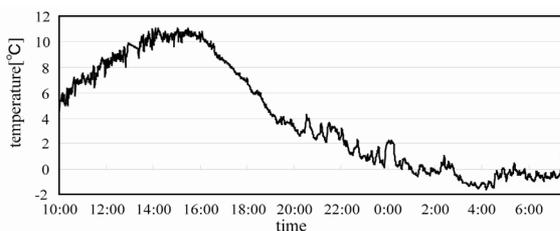


Fig.9: Ambient temperature

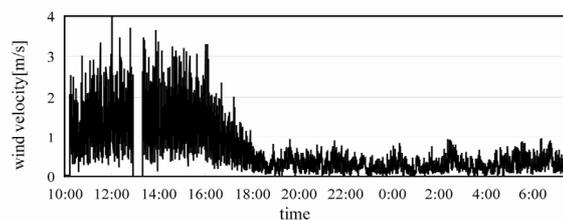


Fig.10: Outside wind velocity

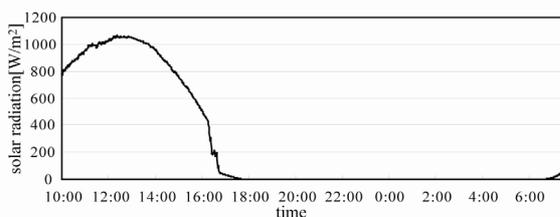


Fig.11: Solar radiation at inclined surface

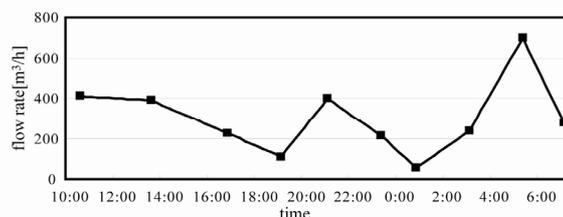


Fig.12: Flow rate calculated from measured concentration of tracer gas

- 1) Tracer gas is not diffused enough inside the chimney.
- 2) The air velocity is not uniform at every point in the chimney.
- 3) All tracer gas did not reach the measurement point of the gas concentration.

Due to these problems, low values of tracer gas concentration could be measured and resulted in a large flow rate. More accurate measurement method of tracer gas should be developed in the future. Furthermore the influence of the outdoor wind on the airflow in the chimney should be accounted for by measuring the wind pressure at the inlet and outlet opening areas.

5. NUMERICAL SIMULATION MODEL OF SOLAR CHIMNEYS

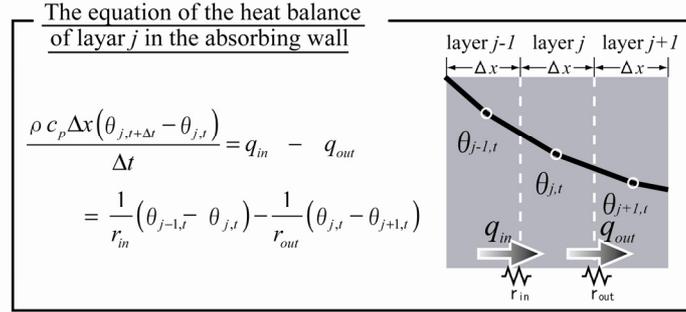


Fig.13: Heat balance at layer j in the absorbing wall

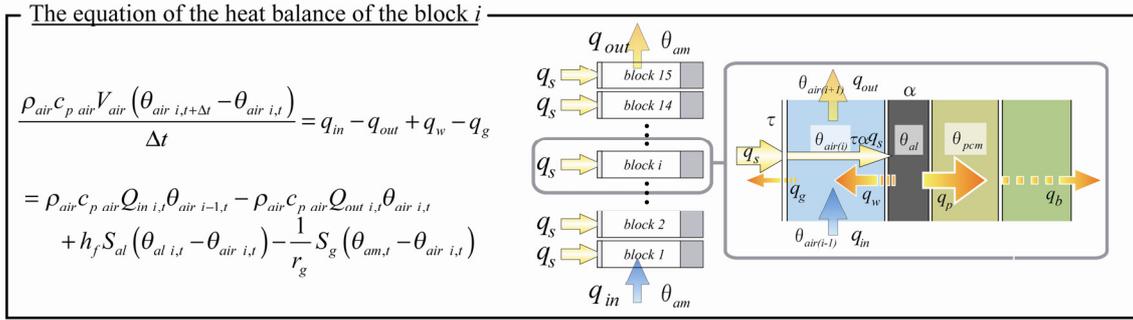


Fig.14: Heat balance at block i in the chimney

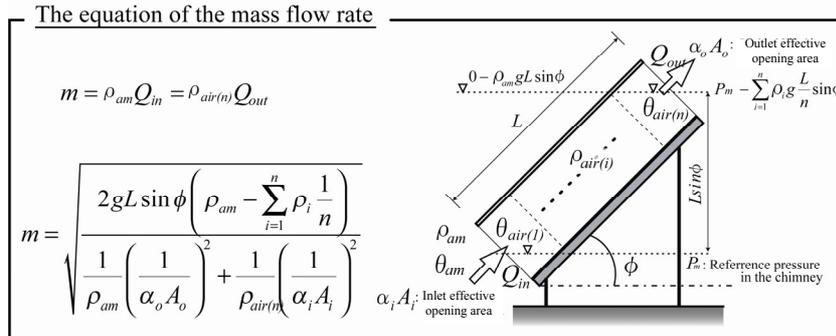


Fig.15: Ventilation at the opening area

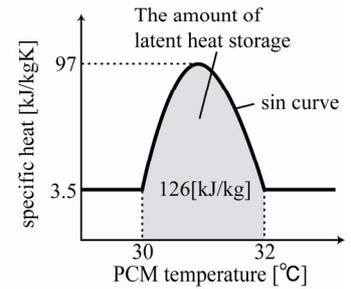


Fig.16: Changing property of PCM's specific heat

Table2: Value of inputs

Length of the chimney [m]	1.4	Overall absorptance of the absorber [-]	0.94	
Air gap [m]	0.2	Transmittance of glazing [-]	0.9	
Width of the chimney [m]	0.85	Convective heat transfer coefficient [W/m ² K]	15	
Inclination angle [degree]	45	Heat conductivity[W/mK]	Glazing	0.78
Inlet and outlet opening area [m ²]	0.17		Al-plate	204
Inlet discharge coefficient [-]	0.84		Polystyrene foam	0.03
Outlet discharge coefficient [-]	3.37		Container	0.13

The numerical simulation was conducted to predict the temperature and airflow rate inside the solar chimney. The control volume method on the heat capacity is used in the absorbing wall and a forward differential method is used on the time step. It is assumed that the elements in the absorbing wall are divided into some layers (control volumes) and its heat capacity is concentrated on the center of every layer. In this paper PCM is divided into 10 layers, the insulation material into 5 layers, aluminum (Al) plate into one layer, and the container of PCM into one layer. The temperature in every layer is calculated by the heat balance equations between the control volumes in the elements. (see Fig.13). The air volume inside the chimney is divided into 15 blocks along the direction of air flow (see Fig.14). The input of the calculation is the incident solar radiation and ambient air temperature. The flow rate and the temperature of every element in the chimney are calculated by the heat balance equation at every elements and the equation of the mass flow rate at the inlet and outlet opening (see Fig.15). The phase changing of PCM is simulated by an enthalpy method [3]. The latent heat is assumed to be distributed between 30 and 32 degree C of PCM temperature and the amount of heat storage with phase changing is analyzed using the heat capacity which the latent heat of PCM was taken into consideration. In this paper the specific heat of PCM is changed with sine curve (see Fig.16). It is assumed that no convective flow occurs inside PCM modules, even if PCM melts. And convective heat transfer coefficient (h_f) is defined as a constant value of 15 [W/m² K] and it is assumed that no radiation heat transfer occurs in the chimney.

6. SIMULATION RESULT AND DISCUSSION

The airflow rate and temperatures of PCM, Al-plate and air in the chimney are shown in Fig.17.

Simulated results for temperature of Al-plate and air in the chimney well agreed with experimental results from evening to morning (from 17:00 to 7:00). In the daytime, the simulated Al-plate temperature is higher than the measured value and the simulated air temperature inside the chimney is lower than measured one.

This difference seems to be caused by the difference of convective heat transfer coefficient between simulation and measurement. It was defined as constant value of 15 [W/m² K] in the simulation. It seems that larger value of the convective heat transfer coefficient should be given in this model. Furthermore, the temperature of Al plate will be lower and simulated result will agree with the measurement value, if radiation heat transfer in the chimney is considered. It is necessary to account for the influence of the radiation heat transfer and more suitable value of the convective heat transfer coefficient in the future study.

Simulated PCM temperature shows the good agreement with the experimental result. In the phase changing process, some differences are found between the simulation and the measurement during the freezing process although the simulated result during the melting process shows good agreement with the measured result. It seems that these differences are due to no modeling of the super cooling that causes a drop in temperature at the freezing process.

The simulated result for the flow rate is stable during all day. On the other hand, the measured flow rate is changing every time in the night. This difference between the simulation and the measurement seems to be caused by the outdoor wind that is ignored in the simulation. In the future study, therefore, the modeling of the flow rate induced by the wind is desired.

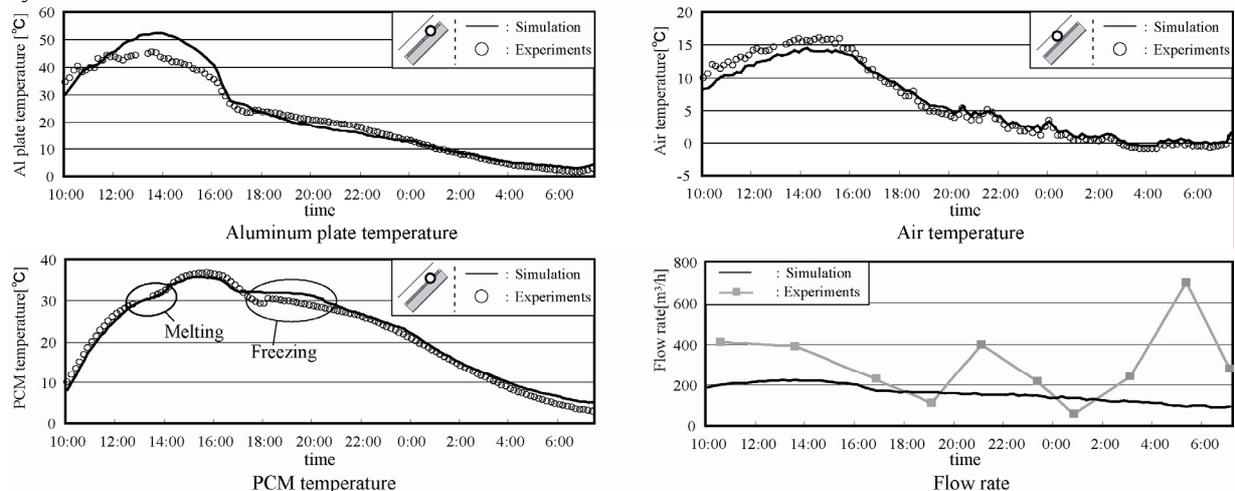


Fig.17: Simulation result and experiments

7. CONCLUSION

Solar chimney with built-in latent heat storage material for prolongation of the natural ventilation in evening / night time has been developed. It was observed from the temperature variation of PCM, Al-plate and air in the chimney that integration of PCM storage inside the solar chimney was available for the natural ventilation in the evening and night, if PCM completely melt in the daytime. From the measured result of the flow rate in the prototype of the chimney, it was found that the prototype chimney supply the airflow rate of 100 to 400 m³/h that might include the flow rate induced by the wind. It seems that this measurement technique of the gas concentration had some problems. It is necessary to consider how to measure the accurate gas concentration. Influence of the outdoor wind should be investigated as well by measuring the wind pressure at the opening areas of the chimney in the future. Simulated results of the temperature as a whole were agreed with the measurement results. To improve the precision of the numerical model, the following matters should be considered in the future;

1. The appropriate value of the convective heat transfer coefficient
2. The influence of the radiative heat transfer
3. The flow rate induced by the outdoor wind

ACKNOWLEDGEMENT

A part of this work was supported by Grants for the Exploratory Research of Ministry of Education, Culture, Sports, Science and Technology (No.17656183, 2005). The provision of the PCM container from SUMIKA PLASTECH Co., Ltd. is gratefully acknowledged.

NOMENCLATURE

A_i, A_o	: Inlet and outlet opening area of solar chimney (m ²)	q_{in}	: Conductive heat flow from aluminum (Al) plate to PCM (W/m ²)
S_{al}	: Area of Al-plate (m ²)	q_b	: Convective heat loss from wall (W/m ²)
S_g	: Area of glazing (m ²)	Q_{in}	: Volume flow rate of air at inlet of chimney (m ³ /s)
$c_{p\ air}$: Specific heat of the air (J/kgK)	Q_{out}	: Volume flow rate of air at outlet of chimney (m ³ /s) (W/m ² K)
c_p	: Specific heat of layer j (J/kgK)	θ_{air}	: Air temperature inside the chimney (degree C)
r_{in}, r_{out}	: Resistance of heat conduction (m ² K/W)	θ_{pcm}	: PCM temperature (degree C)
h_f	: Convective heat transfer coefficient (W/m ² K)	θ_{Al}	: Absorbing aluminum (Al) plate temperature (degree C)
L	: Length of the solar chimney (m2)	θ_{am}	: Ambient air temperature (degree C)
m	: Mass flow rate of air (kg/s)		(Greek letters)
q_s	: Incident global solar radiation on collector (W/m ²)	ρ_{air}	: Air density (kg/m ³)
q_{in}	: Heat flow of air flowing from environment to chimney (W/m ²)	ρ	: Density of layer j (kg/m ³)
q_{out}	: Heat flow of air flowing from chimney to the environment (W/m ²)	α	: Overall absorptance of absorber (-)
q_g	: Heat flow transmitted from glazing to environment (W/m ²)	α_i	: Inlet discharge coefficient (-)
q_w	: Convective heat flow from wall to flowing fluid (W/m ²)	α_o	: Outlet discharge coefficient (-)
		τ	: Transmittance of glazing (-)
		ϕ	: Inclination angle (degree)

REFERENCES

- [1] Adam, Z., Yamanaka, T., Kotani, H., Mathematical model and experimental study of airflow in solar chimneys, *Proc. 8th International Conference on Air Distribution in Rooms (ROOMVENT 2002)*, pp.621-624, 2002
- [2] Adam, Z., Yamanaka, T., Kotani, H., Simulation study on solar assisted ventilation systems, *Journal of Environmental Engineering, Architectural Institute of Japan (AIJ)*, pp.19-26, 2004
- [3] Saito, T., Computer-Aided Heat Transfer, *Yokendo, 1992 (in Japanese)*