Penerbit Akademia Baru

International Journal of Solar Thermal Vacuum Engineering

Journal homepage: www.akademiabaru.com/stve.html
ISSN: 2716-6953

Analysis of indoor environment and performance of net-zero energy building with vacuum glazed windows

Takao Katsura[1,*], Haruhiko Ito[2], Kirina Komuro[3], Katsunori Nagano[1], Saim Memon[4]

[1] Division of Environmental Engineering, Faculty of Engineering, Hokkaido University, Sapporo, Japan
[2] ARIGA Kougyou Sho Co.,LTD, Sapporo, Japan
[3] Division of Human Environmental Systems, Graduate School of Engineering, Hokkaido University, Sapporo, Japan
[4] Solar Thermal Vacuum Engineering Research Group, London Centre for Energy Engineering, School of Engineering, London South Bank University, London, United Kingdom

ABSTRACT

The total energy and indoor thermal environment of an office building, which aims at the net-zero energy building, were measured and analysed. The annual total primary energy consumption of 'Measurement' was smaller than the value of 'Calculation' at design phase and achieved net-zero. The result of analysis of the thermal environment shows that the comfortable thermal environment was maintained. Also, the insulation performance and heat balance of the vacuum glazed windows in winter was evaluated. The overall heat transfer coefficients calculated by using the monitoring data were almost equal to the rated overall heat transfer coefficient and the high insulation performance of vacuum glazed windows was maintained even in the second year's operation. In addition, the amount of heat gain due to solar radiation on the window surface was much larger than the amount of heat loss due to transmission. The vacuum glazed windows with high thermal insulation performance on the south side can reduce the heating load and contribute to the achievement of net-zero in the buildings.

Keywords:
Net-Zero Energy Building; Vacuum glazed windows; Indoor thermal environment; Heat loss and gain

1. Introduction

In order to prevent global warming, which is one of the global environmental problem, reducing the energy consumption of building becomes an important issue [1,2]. As such there are a number of progressive technologies are under investigation for mass deployment, such as translucent vacuum insulation panel [3,4], triple vacuum glazed windows [5-8], advanced vacuum based photovoltaic solar thermal collectors [9] and utilising the waste heat into electricity using thermoelectric [10-12]. The reality of carbon capture and energy storage in buildings has also been investigated [13]. In Japan, with the aim of reducing energy consumption of the building sector, the compliance of energy conservation has begun to be mandatory for newly built non-residential buildings with a total floor area of 2,000 m^2 or more since April 2017. In addition, Net-Zero Energy Building (ZEB) is attracting attention as a building that is more energy efficient than a building that

* *Corresponding author.*
E-mail address: katsura@eng.hokudai.ac.jp

https://doi.org/10.37934/stve.3.1.114

meets the energy conservation standards. ZEB is listed as one of the measures to reduce energy consumption in the building sector. In this paper, the authors measured and analysed an office building completed in Sapporo, Japan in January 2018. This target building is the first building certificated as (ZEB-Net-Zero Energy Building) in the cold climate region in Japan, and several energy-saving technologies have been installed. As the most attractive point, the vacuum glazed windows were applied in all windows facing the outside air.

Vacuum glazed windows has a layer of vacuum insulation which is a space sandwiched between two glass plates [14] and is categorized as one of the vacuum insulation technologies [15]. The first idea of vacuum glazed window was proposed by Zoller in 1913 [16] and the first successful vacuum glazing sample was fabricated by Collins et al in 1989 [17]. In 2000s, Nippon Sheet Glass Group attempted the commercialization of vacuum glazed windows and vacuum glazing products called SPACIA were fabricated [18]. Currently, the market of vacuum glazing windows is dominated by three products supplied form Nippon Sheet Glass Group [19]. With regard to the experimental thermal performance investigation with vacuum glazed windows, Papaefthimiou et al. conducted an experiment with the guarded hot box calorimeter to evaluate the thermal performance of vacuum glazed window and reported the lowest U-value (Overall heat transfer coefficient) of 1.17 W $m^{-2}K^{-1}$ [20]. Additionally, Fang et al. carried out a similar experiment [21]. However, the research works related to the evaluation of vacuum glazed windows installed in the actual building were hardly observed [22]. So far solder glass edge seal for vacuum glazed windows has been successfully at mass manufacturing by SPACIA, however other progressive methods such as laser sealing and bonding glasses mechanisms are being explored [23-25].

In this paper, the authors present the experimentally measured thermal transmission of vacuum glazed windows installed in the office building by using the heat flux meter. In addition, the indoor temperature and the ambient air temperature were measured, and the overall heat transfer coefficient was estimated by using the measurement data. Furthermore, the total energy and indoor thermal environment of this office building were analysed. Then, the contribution of vacuum glazed windows to ZEB was evaluated.

2. Outlines of Net-Zero Energy Building with Vacuum Glazed Windows

2.1. Net-Zero Energy Building

Fig. 1 shows an appearance of ZEB (Office building) with vacuum glazed windows and Table 1 indicated the outlines of ZEB. This office building was completed in Sapporo, Japan in January 2018 and firstly authenticated as (ZEB Net-Zero Energy Building) in the cold climate region in Japan.

Table 1
Outlines of the office building

Location	Sapporo, Japan
Application	Office use
Number of floors	4 Floors
Structure	Steel structure
Site area	606 m^2
Construction area	203.3 m^2
Total floor area	643.9 m^2

Fig. 1. An appearance of the office building with vacuum glazed windows.

The energy saving technologies installed in the office building are indicated in Fig. 2 and Table. 2. The appearance of energy technologies heat recovery ventilation, GCHP, PV system and LED energy efficient lighting system installed is shown in Fig. 3. The envelope performance was improved by the insulation materials, the vacuum glazed windows, and the blind systems. The heat recovery ventilation system was installed and additionally reduces the heating and cooling load [26]. The ground source heat pump system was applied as the heat source for heating and cooling, and it can operate with high efficiency. In addition, the energy for lighting can be saved by the LED lightings and the illuminance control systems. The reduction of energy consumption could be calculated as approx.56% at design phase by combining these energy saving technologies.

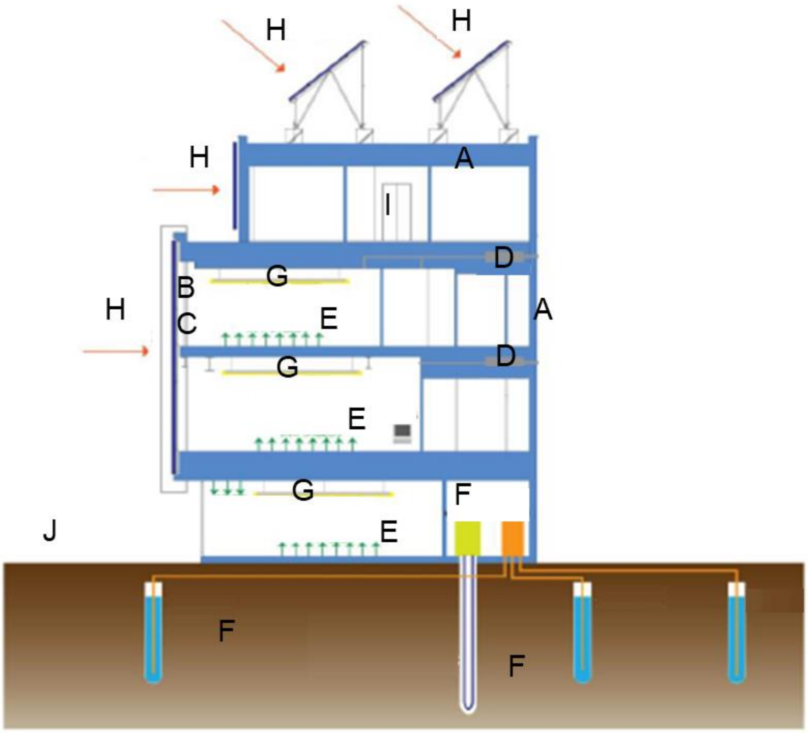

Fig. 2. Energy saving technologies installed in the office building

Table 2
Energy saving components installed characteristics.

	Name	Outline and specification
Envelope	A. Insulation	Urethane foam insulation (Roof: t = 150 mm, Wall: t = 125 mm)
	B. Window insulation	Triple glass with vacuum insulation (Overall heat transfer coefficient: 0.68 W m^{-2} K^{-1} Shading coefficient: 0.5)
	C. Solar shading	Blind system
HVAC system	D. Heat recovery ventilation system	Efficiency of heat recovery (Rated): 70~77%
	E. Air-conditioning system	Floor heating system (1F) Underfloor air-conditioning system (2F, 3F)
	F. Ground source heat pump system	Rated heating/cooling output of heat pump: 34 kW Borehole GHE 100 m × 6 + 3 wells for heat source
Lighting system	G. LED and control system	Control system by applying motion sensor, illuminance sensor, and time schedule
Power supply	H. PV	Rated power generation: 50.88 kW
	I. Battery storage	Total capacity:31.2 kW
Others	Ground source snow melting pavement	

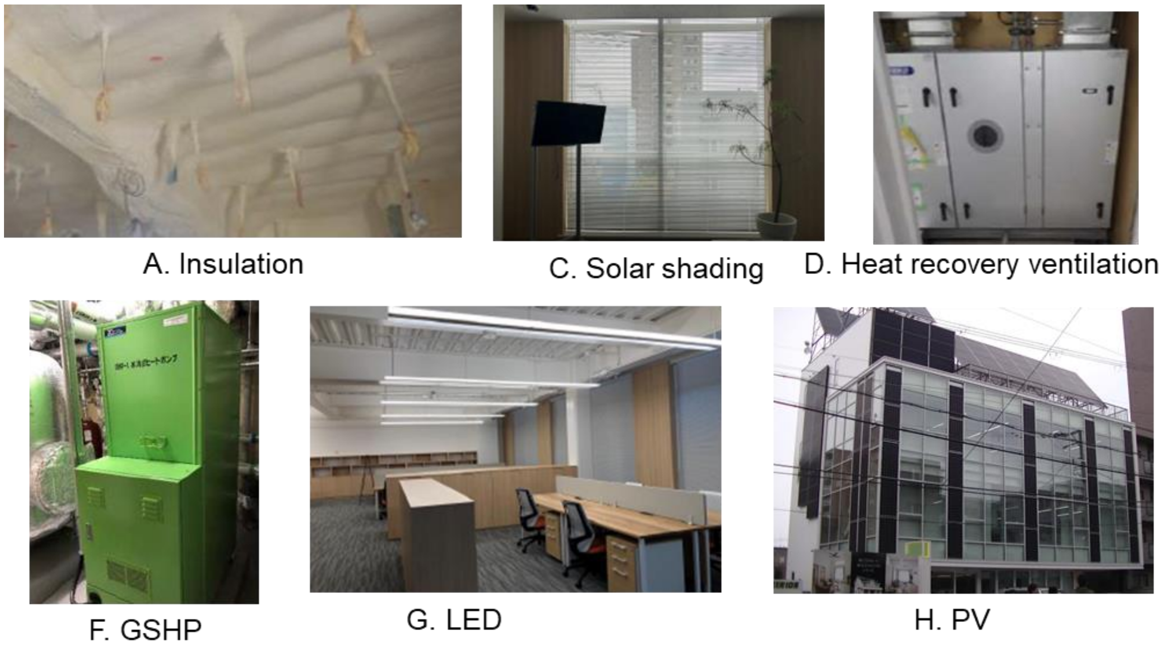

Fig. 3. Illustrates (a) internal insulation, (b) solar shading control blinds, (c) heat recovery ventilation system, (d) Ground Source Heat Pump (GSHP), (e) energy efficient LED lighting and (f) appearance of the installed PV system.

Furthermore, the PV and battery storage system were installed in this building. The electric power generation by PV would be more than the total electric power consumption of building.

2.2. Vacuum glazed windows

The vacuum glazed windows were applied in all windows facing the outside air. The outlines of vacuum glazed window are shown in Fig. 4. The vacuum glazed window consists of three-layer glasses with the thickness of 3 mm. Two of the three glasses have the low-emissivity coating. One of the two layers sandwiched between glasses is the vacuum layer and the other was filled with the Krypton gas. These reduces the heat loss from windows and the rated overall heat transfer coefficient decreases to 0.68 W $m^{-2}K^{-1}$. The shading coefficient is 0.5.

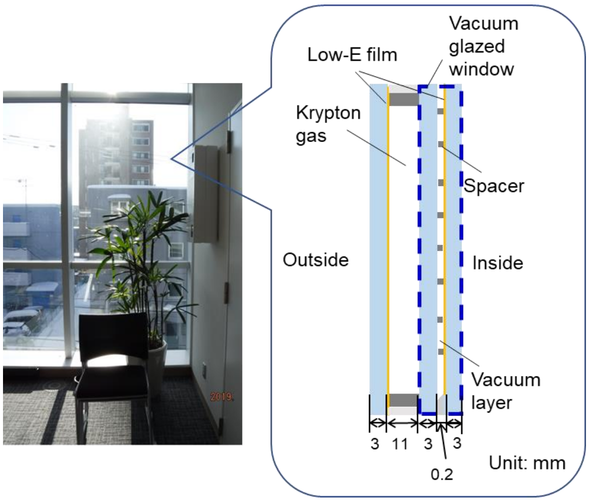

Fig. 4. Outlines of vacuum glazed window

3. Measurement and Analysis Method

3.1. Total energy

The monitoring points by BEMS are indicated in Table 3. The electric power consumption of each item was monitored. Also, the indoor temperature and humidity were monitored. Therefore, the electric power consumption of building was tried to minimize by checking the monitoring data.

Table 3
Monitoring points by BEMS in the office building

	Points and number
Electric energy	Air-conditioning (AC), Ventilation, Lighting (Light), Hot water(HW), Elevator (EV), Photovoltaics (PV), others Total 47 points
Temperature	Indoor temperature, outdoor temperature Total 24 points

3.2. Indoor thermal environment

The sensors independent of BEMS were equipped as shown in Fig. 5 and the indoor thermal environment of this building was evaluated. The specifications of sensors are indicated in Table 4. The temperature difference due to the difference in place was analysed by the temperature sensors 1~5. The vertical temperature distributions at point B and point C were measured by the thermo couples placed at height of 0, 0.1, 1.0, 1.2, 1.8 m. In addition, temperature, globe temperature, humidity and air velocity at point A were measured. By using these measurement data, the mean radiant temperature (MRT) and predicted mean vote (PMV) at point A were calculated. Measurement was carried out from February 7th and 11th in 2019.

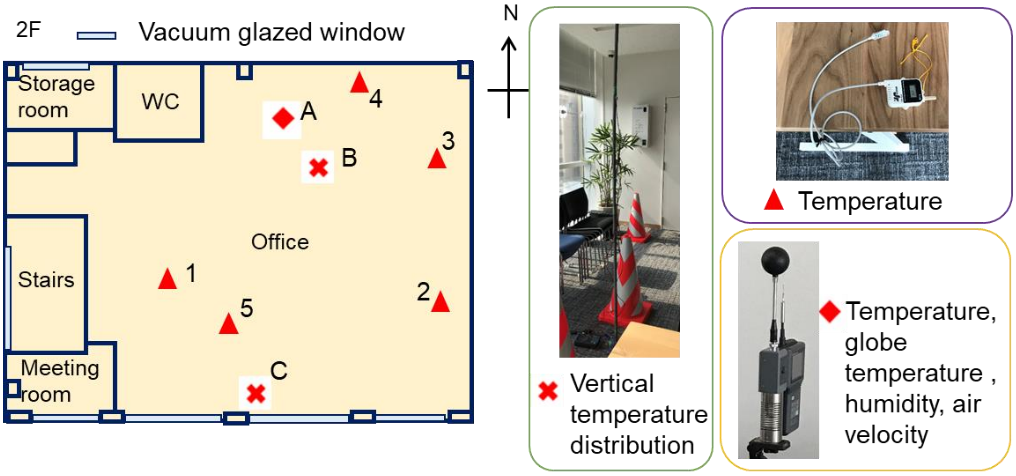

Fig. 5. (Left) Arrangement of sensors to evaluate thermal environment, (Right) Appearance of sensors installed in the office building

Table 4
Sensors to evaluate thermal environment and their measurement accuracy.

	Sensor	Measurement accuracy
Temperature	NTC sensor	±0.5°C
Vertical temperature distribution	Thermo couple (Height : 0, 0.1, 1.0, 1.2, 1.8 m)	±1.0°C
Temperature, globe temperature, humidity, air velocity	NTC sensor (Temperature, globe temperature) Humidity sensor Air velocity sensor	±0.5°C(at15~35°C) ±3%(at20~80%RH) ±0.1 m/s(at 0~1 m/s)

3.3. Heat loss and gain via vacuum glazed windows

A heat flux meter was placed on the south-facing window inside surface as shown in Fig. 6, and the heat loss and heat gain via the window surface were measured. Also, the indoor air temperature and ambient air temperature were monitored. The sensors to evaluate vacuum glazed windows and their accuracy are listed in Table. 5. In the night, there is no heat gain due to the solar radiation and only the heat loss due to heat transmission is generated. Therefore, the overall heat transfer coefficient was evaluated by using the monitoring data of heat flux, indoor air temperature, and ambient air temperature in the night. In the daytime, the value of heat flux changes from negative to positive due to the solar radiation. The heat balance of the vacuum glazed windows in winter was analysed by applying the measured value of the heat flux in the daytime. Measurement was carried out from February 17th to March 5th (2nd floor) and from March 5th to March 20th (3rd floor) in 2019. In order to verify the long-term performance, additional measurement was carried out from December 10th to December 27th (2nd floor) in 2019.

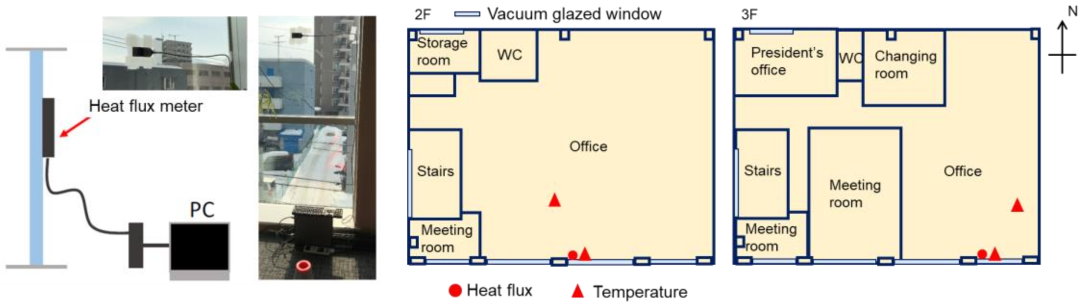

Fig. 6. (Left) Outlines and appearance of measuring heat flux, (Centre and Right) Arrangement of sensors to evaluate vacuum glazed windows.

Table 5
Sensors t to evaluate vacuum glazed windows and their measurement accuracy.

	Sensor	Measurement accuracy
Temperature	NTC sensor	±0.5°C
Heat flux	Heat flux meter	±2%

4. Result and discussion

4.1. Total energy

Fig. 7 shows the monthly primary energy consumption. It can be seen that the primary energy consumption for air-conditioning (AC) increases and the amount of power generation from PV decreases in winter season. The amount of power generation from PV is smaller than the total energy consumption from November to February. On the other hand, the amount of power generation is lager from March to October. Table 6 compares the annual primary energy consumptions of ‘Baseline’, ‘Calculation’, and ‘Measurement’. Here, ‘Baseline’ and ‘Calculation’ indicate the annual primary energy consumption of standard building and this building, calculated at the time of design. The annual total primary energy consumption of ‘Measurement’ is smaller than the value of ‘Calculation’. Especially for air-conditioning (AC) and Lighting (Light), the values of ‘Measurement’ are significantly smaller. This is due to the users’ consideration for energy saving. Also, the annual primary energy consumption of ‘measurement’ was reduced by more than 60% compared to the value of ‘Baseline’ in all items except for others and the total achieved net-zero. In Japan, when the net energy consumption becomes less than zero except for others as shown by ‘Calculation’, the building is certified as (ZEB). However, the net energy consumption achieved zero even if ‘Others’ was included in ‘Measurement’.

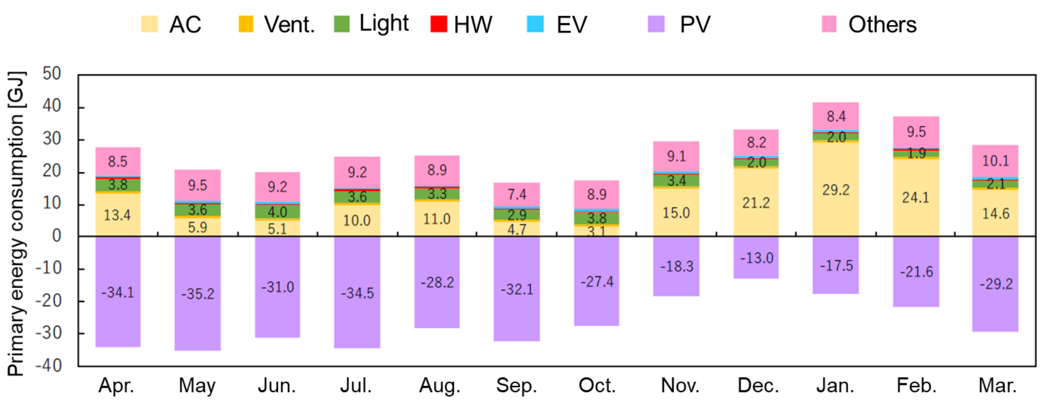

Fig. 7. Monthly primary energy consumption in FY2018

Table 6
Annual primary energy consumptions of ‘Baseline’, ‘Calculation’, and ‘Measurement’ in FY2018 and reduction rate of primary energy consumption

Primary energy consumption [GJ/year]									
	AC	Vent.	Light.	HW	EV	PV	Others	Total	Total except others
A. Baseline	457.34	40.28	219.34	22.85	24.00	0	120.38	865.9	745.5
B. Calculation	218.31	8.39	71.87	5.81	21.33	-376.66	120.38	69.4	-51.0
C. Measurement	157.3	8.4	36.4	5.9	7.3	-322.1	106.8	0	-106.9
1 - B / A	0.522	0.791	0.672	0.746	0.111	-	0	0.919	1.068
1 - C / A	0.656	0.790	0.833	0.742	0.697	-	0.113	1.000	1.143

4.2. Indoor thermal environment

As measurements result on the representative day, Fig. 8 shows the variations of indoor air temperature at point 1~5 indicated in Fig. 5 and ambient air temperature on February 8th and 9th in 2019. February 8th was the coldest day of 2019 in Sapporo. The room temperature became the lowest around 8:00, when heating started, and reached 15~17^{o}C. After the start of heating, the temperature rose and reached 20^{o}C around 12:00. The temperature difference at each measurement point was 2^{o}C or less, and it was confirmed that the temperature difference was small in the interior. As shown in Fig. 9 is the variations of indoor air temperature, MRT, and PMV at point A indicated in Fig. 5 on February 8th and 9th in 2019. The MRT was almost equal to the indoor air temperature. PMV increased with temperature rising and became larger than -0.5 in the time zone above 20^{o}C. Fig. 10 are the vertical temperature distributions at point B (Perimeter zone) and point C (Interior zone) indicated in Fig. 5 on February 8th in 2019. Except for 12:00, the temperature at point C is approximately 2^{o}C higher than that at point B. In addition, the temperature at height of 0 and 0.1 m is almost the same as the others at point B and the temperature at height of 0 and 0.1 m is approximately 1^{o}C higher at point C. From this, it was confirmed that the underfloor air-conditioning could prevent the temperature decrease at the feet. It can be said that the comfortable thermal environment was maintained even though the temperature in the morning was low because of the users’ highly conscious for energy saving.

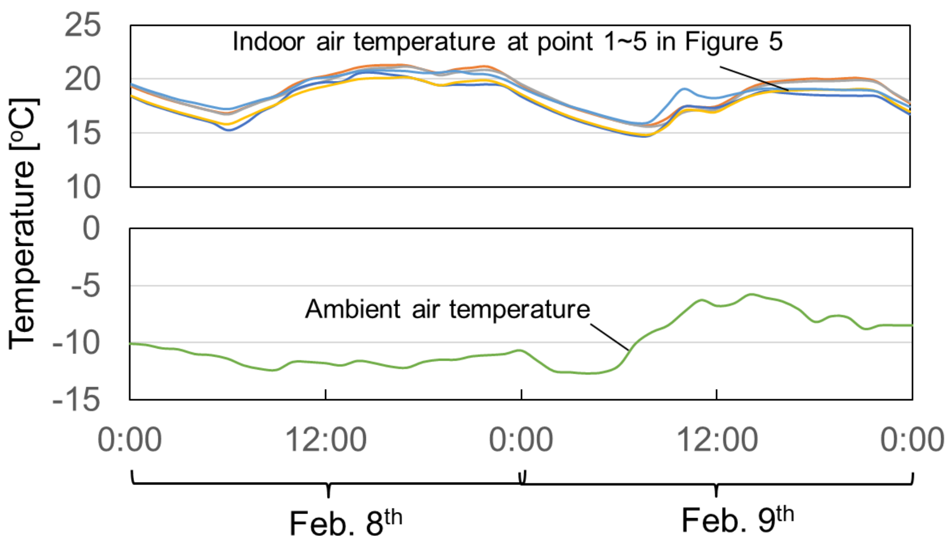

Fig. 8. Variations of indoor air temperature at point 1~5 indicated in Fig. 5 and ambient air temperature on February 8th and 9th in 2019

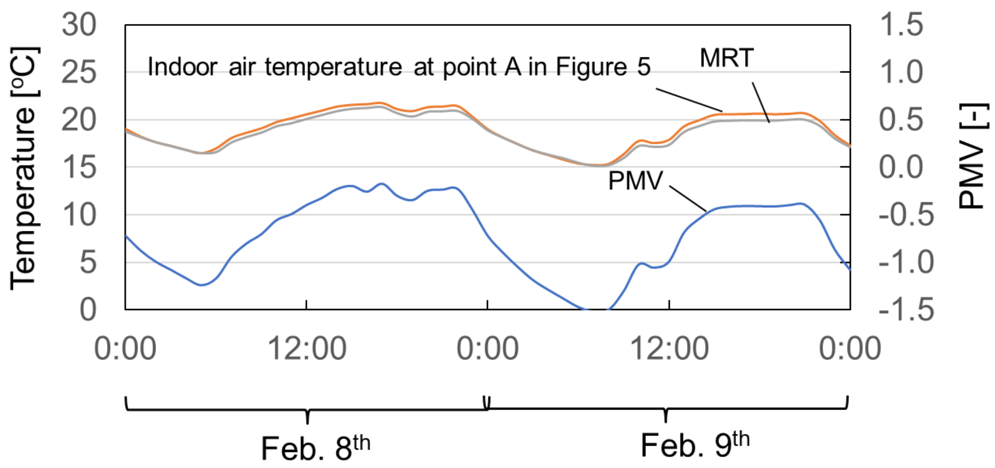

Fig. 9. Variations of indoor air temperature, MRT, and PMV at point A indicated in Figure 5 on February 8th and 9th in 2019

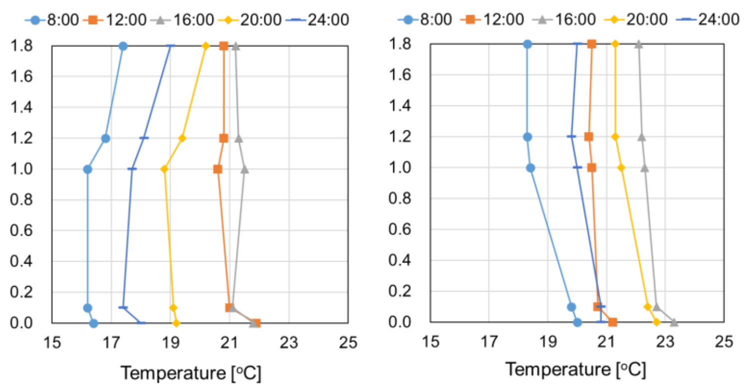

Fig. 10. Vertical temperature distributions at point B (Perimeter zone, left) and point C (Interior zone, right) indicated in Fig. 5 on February 8th in 2019.

4.3. Heat loss and gain via vacuum glazed windows

As measurement results at night on the representative day, Fig. 11 show the variations of heat flux, indoor air temperature, and ambient air temperature. It can be seen that there is no large variation of heat flux. By using the measurement result, the average overall heat transfer coefficient was calculated. The average overall heat transfer coefficients of centre of vacuum glazed windows were estimated as 0.64 W $m^{-2}K^{-1}$ (Fig. 11(a), 0.62 W $m^{-2}K^{-1}$), (Fig. 11(b), 0.62 W $m^{-2}K^{-1}$) and Fig. 11(c), respectively. These overall heat transfer coefficients were almost equal to the rated overall heat transfer coefficient 0.68 W $m^{-2}K^{-1}$. In addition, there was no decrease of average overall heat transfer coefficient between Fig. 11(a) and Fig. 11(c). This result indicates that the high insulation performance of vacuum glazed windows was maintained even in the second year's operation.

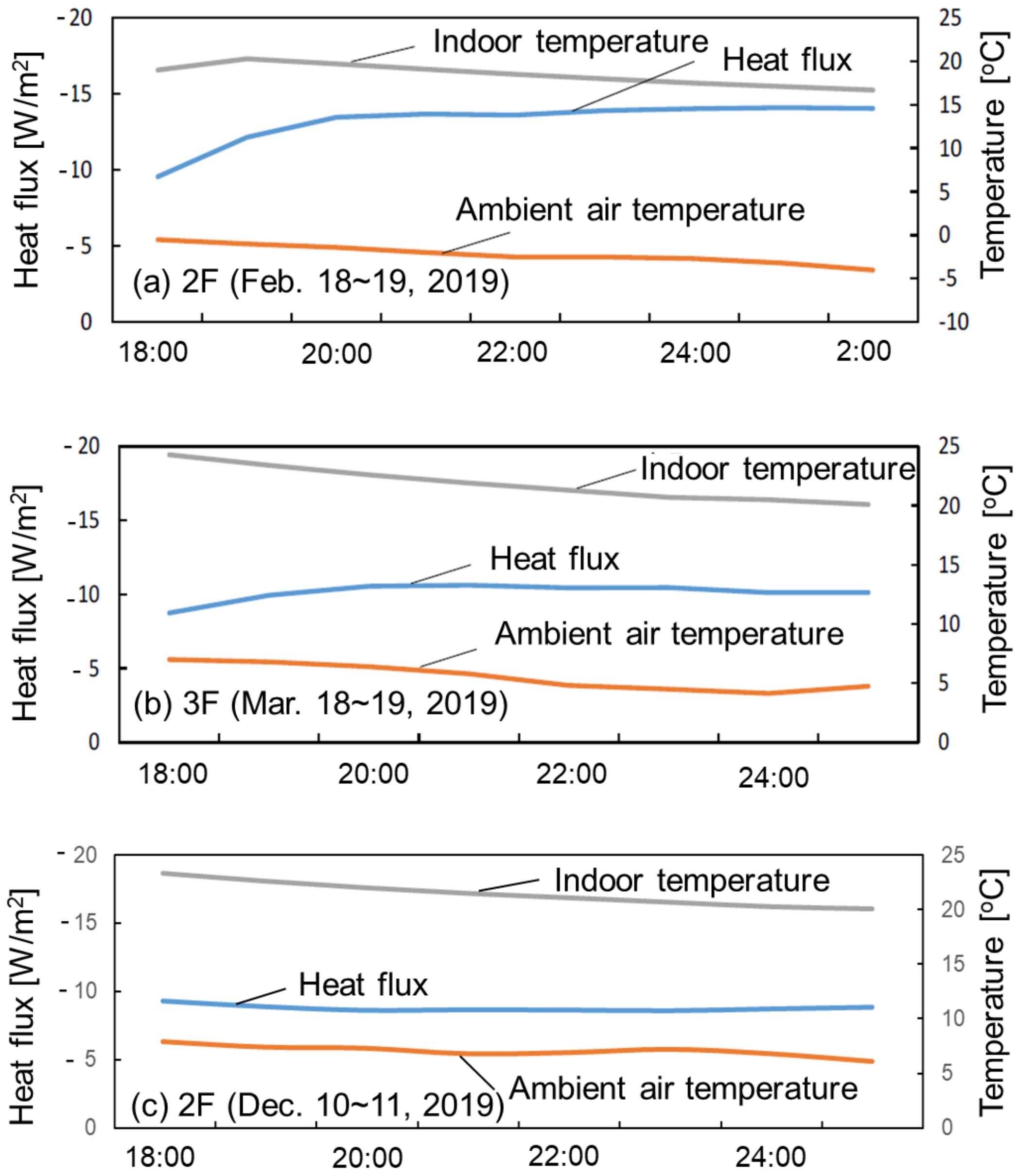

Fig. 11. Variations of heat flux, indoor air temperature, and ambient air temperature ((a) 2F (Feb. 18~19, 2019), (b) 3F (Mar. 18~19, 2019), (c) 2F (Dec. 10~11, 2019))

Next, Figure 12 introduce the variations of heat flux, surface temperature on window. The calculated values of heat gain are also indicated in Fig. 12. Here, the heat gain Q_{gain} is calculated by the following equation.

$$Q_{gain} = I \times \alpha \times \eta$$

The vertical solar radiation on the south side I is calculated by using the measurement value of horizontal solar radiation. The absorption rate of solar radiation α and the shading coefficient of window η are the constants ($\alpha = 0.9, \eta = 0.5$). Comparing the measured values with the calculated values, it was confirmed that the errors between the measured values and the calculated values were within 20% on both the 2nd and 3rd floors. Therefore, it can be said that the heat gain due to solar radiation can be estimated.

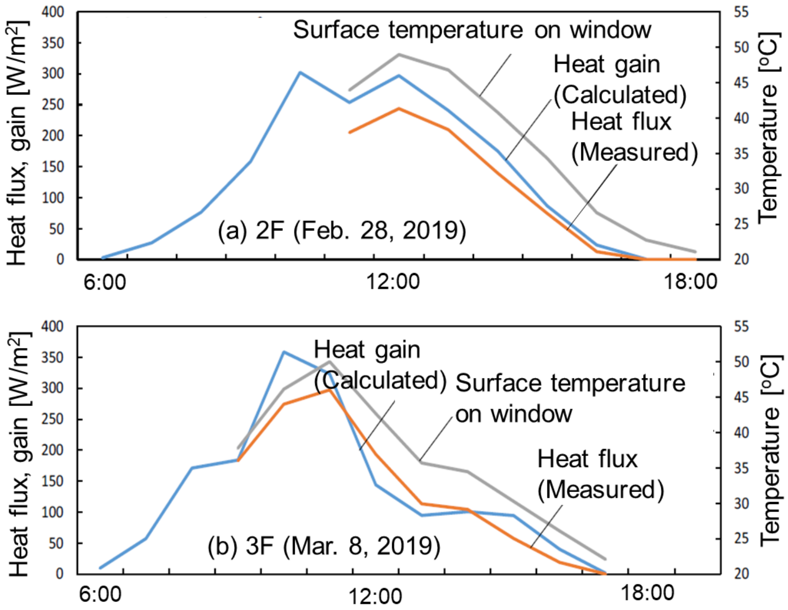

Fig. 12. Variations of variations of heat flux, surface temperature on window, and calculated heat gain ((a) 2F (Feb. 28, 2019), (b) 3F (Mar. 8, 2019)

The amount of heat gain due to solar radiation on the window surface in winter was calculated by using the vertical solar radiation, and the amount of heat gain was compared to the heat loss due to the transmission on the window. Fig. 13 is the monthly average ambient air temperature and vertical solar radiation on the south side and Fig. 14 shows the amount of heat gain due to solar radiation and heat loss due to transmission from inside to outside. In every month, the amount of heat gain due to solar radiation was larger than the amount of heat loss due to transmission, and the total amount of heat gain in winter was 218.5 kWh m^{-2}, and the total amount of heat loss was 51.6 kWh m^{-2}. From the above, it was found that even in cold regions, the vacuum glazed windows with high thermal insulation performance on the south side can reduce the heating load and contribute to the achievement of net-zero in the buildings.

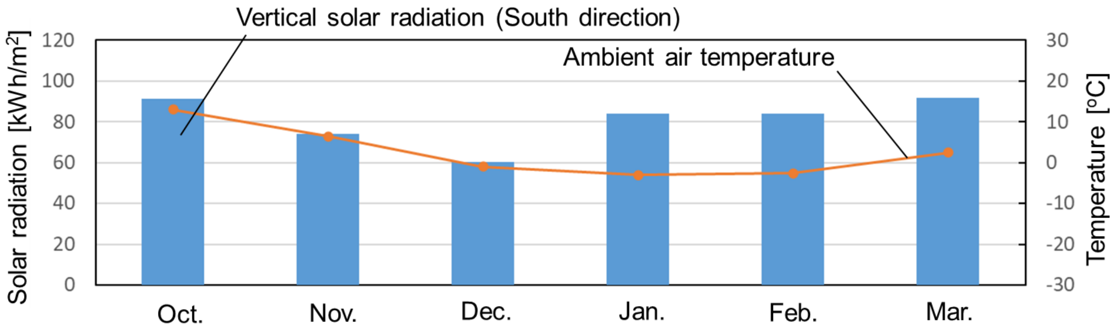

Fig. 13. Monthly average ambient air temperature and vertical solar radiation on the south side

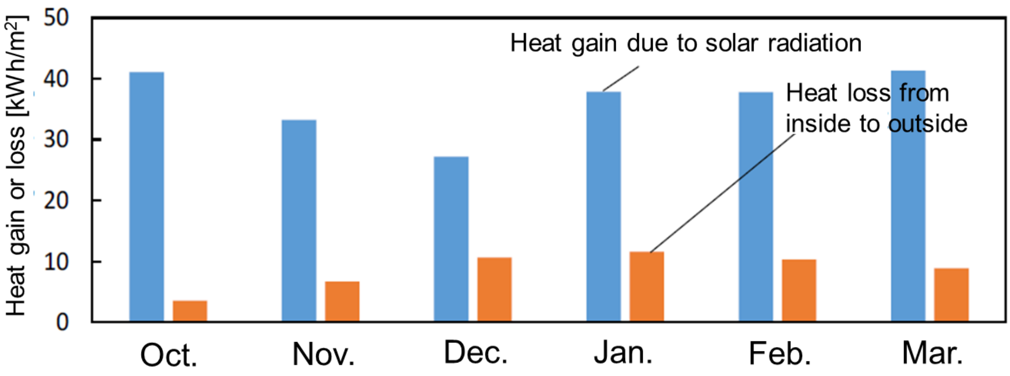

Fig. 14. Amount of heat gain due to solar radiation and heat loss due to transmission

5. Conclusions

The total energy and indoor thermal environment of an office building, which aims at the net-zero energy building, were measured and analysed. Also, the insulation performance and heat balance of the vacuum glazed windows in winter was evaluated. As the results, the following findings were obtained.

1) The annual total primary energy consumption of 'Measurement' was smaller than the value of 'Calculation' at design phase and achieved net-zero even when the annual primary energy consumption of 'Others' was included. This is due to the users' consideration for energy saving.

2) In the coldest day in Sapporo, the room temperature became the lowest around 8:00, when heating started, and reached 15~17°C. However, the temperature rose and reached 20°C around 12:00 after the start of heating. Then, PMV increased with temperature rising and became larger than -0.5 in the time zone above 20°C. The comfortable thermal environment was maintained even though the temperature in the morning was low because of the users' highly conscious for energy saving.

3) These overall heat transfer coefficients calculated by using the monitoring data were almost equal to the rated overall heat transfer coefficient and the high insulation performance of vacuum glazed windows was maintained even in the second year's operation. In addition, the amount of heat gain due to solar radiation on the window surface was much larger than the amount of heat loss due to transmission. Therefore, the vacuum glazed windows with high thermal insulation performance

on the south side can reduce the heating load and contribute to the achievement of net-zero in the buildings.

Acknowledgements

This work was supported by Daiwa Anglo-Japanese Foundation Grant (12549/13360) (Project leader: Dr Saim Memon and Project partner: Dr Takao Katsura).

References

[1] Katsura, Takao, Saim Memon, Ali Radwan, Makoto Nakamura, and Katsunori Nagano. "Thermal performance analysis of a new structured-core translucent vacuum insulation panel in comparison to vacuum glazing: Experimental and theoretically validated analyses." *Solar Energy* 199 (2020): 326-346. https://doi.org/10.1016/j.solener.2020.02.030

[2] Memon, S., T. Katsura, A. Radwan, S. Zhang, A. A. Serageldin, E. M. Abo-Zahhad, S. Sergey et al. "Modern eminence and concise critique of solar thermal energy and vacuum insulation technologies for sustainable low-carbon infrastructure." *International Journal of Solar Thermal Vacuum Engineering* 1, no. 1 (2020): 52-71. ISSN online (2716-6953). https://doi.org/10.37934/stve.1.1.5271

[3] Radwan, Ali, Takao Katsura, Saim Memon, Ahmed A. Serageldin, Makoto Nakamura, and Katsunori Nagano. "Thermal and electrical performances of semi-transparent photovoltaic glazing integrated with translucent vacuum insulation panel and vacuum glazing." *Energy Conversion and Management* 215 (2020): 112920. https://doi.org/10.1016/j.enconman.2020.112920

[4] Ahmed, Mostafa, Ali Radwan, Ahmed Serageldin, Saim Memon, Takao Katsura, and Katsunori Nagano. "Thermal Analysis of a New Sliding Smart Window Integrated with Vacuum Insulation, Photovoltaic, and Phase Change Material." *Sustainability* 12, no. 19 (2020): 7846. https://doi.org/10.3390/su12197846

[5] Memon, Saim, and Philip C. Eames. "Heat load and solar gain prediction for solid wall dwellings retrofitted with triple vacuum glazing for selected window to wall area ratios." In *World Renewable Energy Forum, WREF 2012*, vol. 6, pp. 4636-4643. ASES, 2012. ISBN: 9781622760923

[6] Memon, Saim. "Thermal Conductivity Measurement of Vacuum Tight Dual-Edge Seal for the Thermal Performance Analysis of Triple Vacuum Glazing." *Impact of Thermal Conductivity on Energy Technologies* (2018): 133. http://dx.doi.org/10.5772/intechopen.74255

[7] Memon, Saim. "Design, development and thermal performance analysis of ultra-low heat loss triple vacuum glazing." In *Solar World Congress 2017-Innovation for the 100% renewable energy transformation*. Abu Dhabi. (2017) ISBN 978-3-981 465 9-7-6. https://doi.org/10.18086/swc.2017.15.04

[8] Memon, Saim. "Investigating energy saving performance interdependencies with retrofit triple vacuum glazing for use in UK dwelling with solid walls, Sustainable Development on Building and Environment." In *Sustainable Development on Building and Environment: Proceedings of the 7th International Conference,* 2015. ISBN-13: 978-0993120701.

[9] Radwan, Ali, Takao Katsura, Saim Memon, Essam M. Abo-Zahhad, O. Abdelrehim, Ahmed A. Serageldin, Mohamed R. Elmarghany, Asmaa Khater, and Katsunori Nagano. "Development of a new vacuum-based photovoltaic/thermal collector, and its thermal and exergy analyses." *Sustainable Energy & Fuels* 4, no. 12 (2020): 6251-6273. https://doi.org/10.1039/D0SE01102A

[10] Memon, Saim. "Advanced Thermoelectric Materials for Energy Harvesting Applications." .*IntechOpen Publisher*, London, ISBN: 978-1-78984-529-7, (2020). https://doi.org/10.5772/intechopen.77430

[11] Memon, Saim. "Introductory Chapter: Introduction to Advanced Thermoelectric Materials for Energy Harvesting Applications", Advanced Thermoelectric Materials for Energy Harvesting Applications, *IntechOpen*, London. (2019). https://doi.org/10.5772/intechopen.89640

[12] Memon, Saim, Maekele Mihreteab, Takao Katsura, Ali Radwan, Shanwen Zhang, Ahmed A. Serageldin, and Essam M. Abo-Zahhad. "Experimental and theoretical performance evaluation of parabolic trough mirror as solar

thermal concentrator to thermoelectric generators." *International Journal of Solar Thermal Vacuum Engineering* 1, no. 1 (2020): 22-38. ISSN online (2716-6953). https://doi.org/10.37934/stve.1.1.2238

[13] Memon, Saim, Gemeda Olani Nemera, and Tochukwu Israel Nwokeji. "Manifestations of carbon capture-storage and ambivalence of quantum-dot & organic solar cells: An indispensable abridged review." *International Journal of Solar Thermal Vacuum Engineering* 2, no. 1 (2020): 40-58. https://doi.org/10.37934/stve.2.1.4058

[14] Memon, Saim, and Philip C. Eames. "Design and development of lead-free glass-metallic vacuum materials for the construction and thermal performance of smart fusion edge-sealed vacuum glazing." *Energy and Buildings* (2020): 110430. https://doi.org/10.1016/j.enbuild.2020.110430

[15] Memon, Saim, Yueping Fang, Essam Mohamed Abo-Zahhad, O. Abdelrehim, Mohamed R. Elmarghany, Abdul Rashid Memon, Shanwen Zhang, and Amos Darko. "Factors influencing the performance parameters of vacuum glazed smart windows to net zero energy buildings." *International Journal of Solar Thermal Vacuum Engineering* 2, no. 1 (2020): 1-18. https://doi.org/10.37934/stve.2.1.118

[16] Zoller F. "Hollowpaneofglass." Germanpatentno.387655 (1924)

[17] Robinson, S. J., and R. E. Collins. "Evacuated windows-theory and practice." In *ISES solar world congress, international solar energy society, Kobe, Japan*. 1989.

[18] Fang, Yueping, Saim Memon, Jingqing Peng, Mark Tyrer, and Tingzhen Ming. "Solar thermal performance of two innovative configurations of air-vacuum layered triple glazed windows." *Renewable Energy* 150 (2020): 167-175. https://doi.org/10.1016/j.renene.2019.12.115

[19] Nippon Sheet Glass Group. "Vacuum glazed windows SPACIA." https://shinku-glass.jp/ (In Japanese)

[20] Papaefthimiou. S, G. Leftheriotis, P. Yianoulis et al. "Development of electrochromic evacuated advanced glazing." Energy and Buildings 38 (2006): 1455-1467. https://doi.org/10.1016/j.enbuild.2006.03.029

[21] Fang. Y, T. Hyde, N. Hewitt, P. C. Eames, B. Norton. "Comparison of vacuum glazing thermal performance predicted using two and three-dimensional models and their experimental validation." Solar Energy Materials & Solar Cells 93 (2009): 1492-1498. https://doi.org/10.1016/j.solmat.2009.03.025

[22] Memon, Saim. 2021. "The Scope of Advanced Smart Vacuum Insulation Technologies for Net-Zero Energy Buildings", Sustainable Energy Development and Innovation, WREC 2020. Springer Nature, https://doi.org/10.1007/978-3-030-76221-6

[23] Miao, Hong, Lingcong Zhang, Sixing Liu, Shanwen Zhang, Saim Memon, and Bi Zhu. "Laser Sealing for Vacuum Plate Glass with PbO-TiO2-SiO2-RxOy Solder." *Sustainability* 12, no. 8 (2020): 3118. https://doi.org/10.3390/su12083118

[24] Zhang, Shanwen, Min Kong, Saim Memon, Hong Miao, Yanjun Zhang, and Sixing Liu. "Thermal Analysis of a New Neutron Shielding Vacuum Multiple Glass." *Sustainability* 12, no. 8 (2020): 3083. https://doi.org/10.3390/su12083083

[25] Zhang, Shanwen, Min Kong, Hong Miao, Saim Memon, Yanjun Zhang, and Sixing Liu. "Transient temperature and stress fields on bonding small glass pieces to solder glass by laser welding: Numerical modelling and experimental validation." *Solar Energy* 209 (2020): 350-362. https://doi.org/10.1016/j.solener.2020.09.014

[26] Radwan, Ali, Takao Katsura, Saim Memon, Essam M. Abo-Zahhad, Ahmed A. Serageldin, and Katsunori Nagano. "Analysis of a vacuum-based photovoltaic thermal collector." *Energy Reports* 6 (2020): 236-242. https://doi.org/10.1016/j.egyr.2020.11.255