International Journal of Power Electronics and Drive System (IJPEDS)
Vol. 11, No. 2, June 2020, pp. 1002~1010
ISSN: 2088-8694, DOI: 10.11591/ijpeds.v11.i2.pp1002-1010 ❐ 1002

Theoretical approach model of building integrated photovoltaic thermal air collector

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Article Info

Article history:

Received Mar 1, 2019
Revised Nov 8, 2019
Accepted Jan 23, 2020

Keywords:

Heat transfer
Renewable energy
Solar collector
Thermal modelling

ABSTRACT

Over recent years the photovoltaic technology has obtained significant development, especially in building integrated photovoltaic thermal (BIPVT) system. Photovoltaic thermal (PVT) air collectors are advantageous because of their efficiency. Various studies have been conducted to determine the ideal parameters of PVT air collectors. Few theoretical approach models of PVT air collector systems were used to help detect occurrences in a PVT collector system and calculate the optimal parameters. The heat transfer and energy balance of PVT air collectors were analysed and reviewed based on the model, quantity of cover, channels and forms of the collector. A mathematical model was developed to describe actual working situations and to examine new shut PVT collectors. The first law of thermodynamics is the principal equation in the model. Different analysis methods were utilised to evaluate PVT performances, which are generally based on energy and exergy analyses. This review focuses on theoretical approach model of single-pass PVT air collector.

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1. INTRODUCTION

The depletion of conventional fossil fuel resources has revived the demand for utilisation of renewable energy resources. Therefore, an alternative energy source must be determined to satisfy our energy requirements and preserve conventional fossil fuels. One such renewable energy source is solar energy, which can potentially supply significant amount of the world's energy demand. Renewable energy sources, such as solar energy, provide environmental benefits and clean energy. In addition, solar energy is an ideal alternative source for impoverished or rural people who have no access to modern energy sources. Thermal and electrical energy can be generated from solar energy. Although these two energy sources are have different forms, they can be produced simultaneously by using hybrid collectors. This hybrid system consists of a combination of two types of collectors, namely, thermal collectors and photovoltaic–thermal (PVT) collectors. PVT collectors are designed to receive solar energy and convert it into thermal and electrical energy; in this device, thermal energy is transferred into fluid that flows into the collector. A PVT collector consists of a PV panel, an insulator and a frame as well as one or more cover (glass sheets) or a transparent material placed over the absorbing plate with air flowing around it. The efficiency of PVT collectors can be enhanced by using heat transfer area through the absorber with finned absorbers, corrugated surfaces and porous media. PVT collectors can be classified into four types according to the heat transfer medium: air-based, water-based, combined water/air-based and nanofluid-based PVT collectors [1-13].

The overall performance of the PVT system can be evaluated based on the thermodynamic, environmental and economic impacts analysis. Enviroeconomic and exergoeconomic analyses for PVT air collectors were studied [14]. Environmental-economic-exergy-energy analyses for different PVT air collector systems were studied [15-17]. Several types of PVT air collectors have been designed, evaluated and developed in various countries, thereby yielding varying degrees of technical performances based on energy–exergy analyses. In this review, we focused on the theoretical approach model of single-pass PVT air collector.

2. THEORETICAL APPROACH MODEL OF PVT AIR COLLECTORS WITHOUT GLASS COVER

Sarhaddi et al. [18, 19] improved the thermal and electrical model for a PVT air collector, as shown in Figure 1. The figure shows the cross-sectional view of the PVT air collector, as well as its equivalent thermal resistant circuit and an element length ‘dx’ of the flow channel. The energy balance of the PVT collector is expressed as follows.
For the PV module:

$$\tau_g\left[\alpha_{pv} I \beta_{pv} + \left(1-\beta_{pv}\right)\alpha_T I\right] bdx = \left[h_{pva}\left(T_{pv}-T_a\right) + h_{pvT}\left(T_{pv}-T_T\right)\right] bdx + \eta_{pv} I \beta_{pv} bdx \quad (1)$$

For the back surface of a Tedlar:

$$h_{pvT}\left(T_{pv}-T_T\right) bdx = h_{Tf}\left(T_T-T_f\right) bdx \quad (2)$$

For the air flowing below a Tedlar:

$$h_{Tf}\left(T_T-T_f\right) bdx = \dot{m} C \frac{dT}{dx} dx + U_b\left(T_f-T_a\right) bdx \quad (3)$$

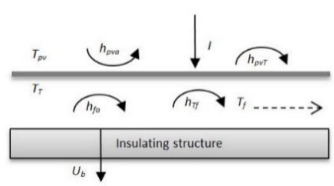

Figure 1. Schematic of temperatures and heat transfer coefficients of a PVT air collector

In the application of PVT system, Sahsavar et al. [20] developed a building integrated photovoltaic (BIPVT) collector by using the cooling potential of ventilation and exhaust air to refrigerate the PV panel and heating system in the ventilation of buildings. The energy balance of this PVT collector, as shown in Figure 2, is expressed as follows.
For PV panels:

$$\alpha_{pv}(1-\eta_{el}) IAdx = \left(h_w + h_{r,pvs}\right)\left(T_{pv}-T_a\right)Adx + h_{pvf}\left(T_{pv}-T_f\right)Adx + h_{r,pvb}\left(T_{pv}-T_b\right)Adx \quad (4)$$

For the air channel:

$$\dot{m}_f C_p dT_f = h_{pvf}\left(T_{pv}-T_f\right)Adx + h_{bf}\left(T_b-T_f\right)Adx \quad (5)$$

For the bottom plate:

$$h_{rpvb}\left(T_{pv}-T_b\right)Adx = U_b(T_b-T_a)Adx + h_{bf}\left(T_b-T_f\right)Adx \quad (6)$$

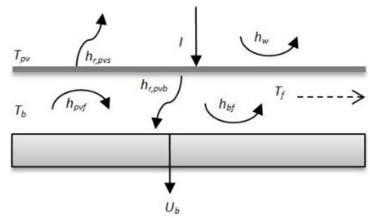

Figure 2. Schematic of heat transfer coefficients and temperatures of a PVT air collector

Sohel et al. [21] proposed a dynamic model for PVT air collectors, as shown in Figure 3. The experimental data were similar with the modelled air temperature and electrical performance. The data from the PVT system were used to authenticate the theoretical approach in two buildings. The system energy balance for the heat loss from the top of the PVT is expressed as follows:

$$Q_{pv} = Ah_{pva}(T_{pv} - T_a) + Ah_{r,pvs}(T_{pv} - T_s). \tag{7}$$

From the PV panel to the air in the channel:

$$Q_{pvf} = Ah_{pvf}(T_{pv} - T_f), \tag{8}$$

From the PV panel to the roof top:

$$Q_{pvr} = Ah_{r,pvr}(T_{pv} - T_r). \tag{9}$$

The system energy balance for the heat loss from air to the roof and from roof to the room is determined as

$$Q_{fr} = Ah_{fr}(T_f - T_r), \tag{10}$$

$$Q_{rrm} = AU_{rrm}(T_r - T_{rm}) \tag{11}$$

The energy balance of the air strip can be calculated as

$$\dot{m}_f C_{pvf} \frac{dT_f}{dx} = Ah_{pvf}(T_{pv} - T_f) - Ah_{fr}(T_f - T_r). \tag{12}$$

The energy balance around an infinitesimal control volume of the PV panel can be calculated as

$$m_{pv}C_{pv}\frac{dT_p}{dt} = (1-\rho).IAM.(1-\eta_{pv})dA.I - Ah_{pva}(T_{pv} - T_a) - Ah_{r,pvs}(T_{pv} - T_s) - Ah_{pva}(T_{pv} - T_a) - Ah_{r,pvr}(T_{pv} - T_r). \tag{13}$$

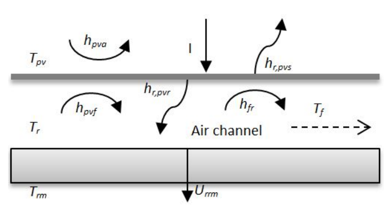

Figure 3. Schematic of heat transfer coefficients and temperatures of a PVT air collector

Vats et al. [22] analysed the energy and exergy performances of a semi-transparent BIPVT system using an integrated PV panel, as shown in Figure 4. The energy balance of this PVT collector is expressed as follows. For the semi-transparent PV module:

$$\tau_g \alpha_{pv} \beta_{pv} IAdx = h_{pva}(T_{pv} - T_a)Adx + h_{pvr}(T_{pv} - T_r)Adx + \eta_{pv} IAdx \quad (14)$$

For the room air temperature:

$$h_{pv,r}(T_{pv} - T_r)A_{pv} + \tau_g^2(1 - \beta_{pv})IA_{pv} = MC\frac{dT_r}{dt} + U_r(T_r - T_a) + 0.33NV(T_r - T_a) \quad (15)$$

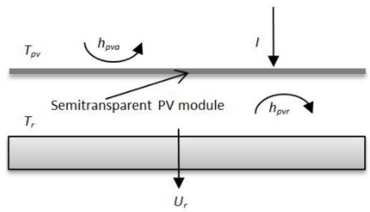

Figure 4. Schematic of heat transfer coefficients and temperatures of a PVT air collector

Yang et al. [23] examined the thermal features of an innovative two-inlet, open-loop BIPVT air collector, as shown in Figure 5. The thermal efficiency of the two-inlet systems was 5% higher than that of a conventional one-inlet system. The thermal efficiency of the BIPVT system with a semi-transparent PV panel reached approximately 7.6%. This system can be easily applied and does not significantly increase cost. The energy balance of this PVT collector is expressed as follows.
For the top PV panel surface:

$$I_{pv} = \frac{A\sigma(T_{pv}^4 - T_{ins}^4)}{\frac{1}{\varepsilon_{pv}} + \frac{1}{\varepsilon_{ins}} - 1} + Ah_{pva}(T_{pv} - T_a) + Ah_{pvf}(T_{pv} - T_f) \quad (16)$$

For the fluid in the BIPVT:

$$\dot{m}C_p(T_o - T_i) = Ah_{pvf}(T_{pv} - T_a) + Ah_{bot}(T_{ins} - T_f) \quad (17)$$

For the lining inner surface:

$$I_{ins} + \frac{A\sigma(T_{pv}^4 - T_{ins}^4)}{\frac{1}{\varepsilon_{pv}} + \frac{1}{\varepsilon_{ins}} - 1} = Ah_{bot}(T_{ins} - T_f) \quad (18)$$

For the PV panel bottom surface:

$$I_{pv} = GAF\alpha_{pv} + GA(1 - F)\alpha_g + GA(1 - F)\tau_g \rho_{ins} \alpha_{pv} - E \quad (19)$$

For the solar radiation incident in the insulation:

$$I_{ins} = GA(1 - F)\alpha_{ins} \tau_g \quad (20)$$

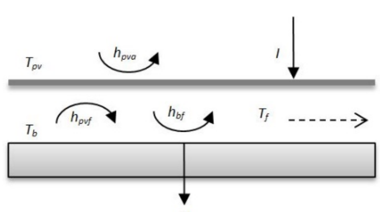

Figure 5. Schematic of temperatures and heat transfer coefficients of a PVT air collector

3. THEORETICAL APPROACH MODEL OF PVT AIR COLLECTORS WITH GLASS COVER

Aste et al. [24] investigated a PVT air collector. A simulation model was developed to calculate the performance of the system. The simulated and experimental thermal and electrical performances of the PVT collector were consistent. The system has been applied to solar rooftops and buildings. The energy balance of this PVT air collector, as shown in Figure 6, is expressed as follows.
For PV cells:

$$IA_{pv}\tau_g\alpha_{pv}\left(1-\frac{\eta^*}{\tau_g\alpha_{pv}}\right)= A_{pv}h_{pva}(T_{pv}-T_a)+A_{pv}h_{pvf}(T_{pv}-T_f)+A_{pv}h_{r,pvp}(T_{pv}-T_p) \quad (21)$$

For the glass part of the sandwich without PV cells inside:

$$IA_g\alpha_g = A_gh_{ga}(T_g-T_a)+A_gh_{gf}(T_g-T_f)+A_gh_{r,gp}(T_g-T_p) \quad (22)$$

For the air gap:

$$M_fC(T_o-T_i) = A_{pv}h_{pvf}(T_{pv}-T_f)+A_gh_{gf}(T_g-T_f)+A_ph_{pf}(T_p-T_f) \quad (23)$$

For the absorber plate:

$$IA_g\tau_g\alpha_p + A_{pv}h_{r,pvp}(T_{pv}-T_p)+A_gh_{r,gp}(T_g-T_p) = A_ph_{pf}(T_p-T_f)+U_bA_p(T_p-T_b) \quad (24)$$

For the PV, the actual thermal–spectral efficiency is

$$\eta^* = \eta_n\frac{100-\gamma(T_{pv}-25)}{100FS}, \quad (25)$$

where γ is the temperature power coefficient of PV cells, and *FS* is the spectrum correction factor of PV efficiency.

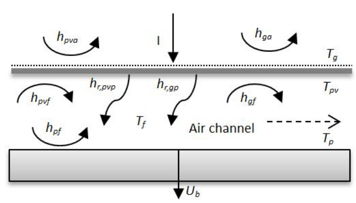

Figure 6. Heat transfer coefficients and temperatures of a PVT air collector

Another heat transfer and energy modelling for PVT air collectors with glass cover were proposed in [25-27]. The analytical expression for the electrical efficiency of PVT hybrid air collectors was established. Case A is a glass-to-glass PV module with an air channel above the absorber plate, and Case B is a glass-to-glass PV module with air channel below the absorber plate. The energy balance of this PVT air collector, as shown in Figure 7, is expressed as follows:
Case A: Glass-to-glass PV module with an air channel above the absorber plate
For the PV module:

$$\alpha_{pv}\tau_g\beta_{pv}S(t)bdx = \left[U_{t,pv}(T_{pv}-T_a)+U_{pv,f}(T_{pv}-T_f)bdx\right]+\tau_g\eta\alpha_{pv}\beta_{pv}S(t)bdx \quad (26)$$

For the blackened absorber plate:

$$\left[\alpha_p\left(1-\beta_{pv}\right)\tau_g^2 I(t)\right]bdx=\left[h_{pf}\left(T_p-T_f\right)+U_{pa}\left(T_p-T_a\right)\right]bdx \quad (27)$$

For air flowing through the channel:

$$\dot{m}_a C_a \frac{dT_f}{dx}dx=\left[h_{pf}\left(T_p-T_f\right)+U_{pvf}\left(T_{pv}-T_f\right)bdx\right] \quad (28)$$

Case B: Glass-to-glass PV module with air channel below the absorber plate
For the PV module:

$$\tau_g\alpha_{pv}\beta_{pv}I(t)bdx=\left[U_{t,pv}\left(T_{pv}-T_a\right)+h_{pvp}\left(T_{pv}-T_p\right)\right]bdx+\tau_g\eta_{pv}\beta_{pv}I(t)bdx \quad (29)$$

For the blackened absorber plate:

$$\left[\alpha_p\left(1-\beta_{pv}\right)\tau_g^2 I(t)+h_{pvp}\left(T_{pv}-T_p\right)\right]bdx=h_{pf}\left(T_p-T_f\right)bdx \quad (30)$$

For the air channel below the absorber plate:

$$\dot{m}_f C_f \frac{dT_f}{dx}dx=h_{pf}\left(T_p-T_f\right)bdx \quad (31)$$

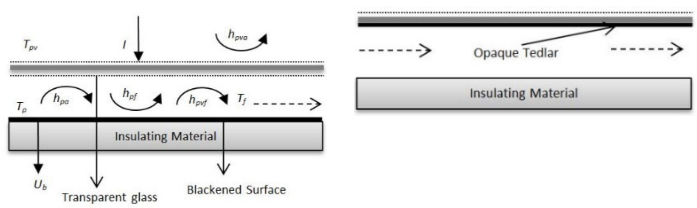

Figure 7. Design and heat transfer coefficients of the system

4. PERFORMANCE OF BIPVT AIR COLLECTOR

Table 1 shows the comparation of Performance of air-based PVT systems.

Table 1. Performance of air-based PVT systems

Year	Author(s)	Study	Performance Analyses	Energy Efficiencies (%)			PVT Exergy Efficiency (%)
				Thermal	PV	Overall	
2007	Alfegi et al. [40]	Experimental	Energy analysis	15.2-26.4	11.4-12.7	26.6-39.13	NA
2008	Alfegi et al. [41]	Experimental	Energy analysis	17-26.43	10.5-12.09	27.5-40.4	NA
2009	Joshi et al. [43]	Experimental	Energy analysis	26.4-30.5	9.5-11	41.6-47.4	NA
2009	Alfegi et al. [44]	Experimental	Energy analysis	NA	NA	49.1-62.8	NA
2009	Dubey et al. [45]	Experimental and theoretical	Energy analysis	NA	NA	9.75–10.41	NA
2010	Agrawal and Tiwari [47]	Experimental and theoretical	Energy–exergy analysis	NA	NA	53.7	NA
2010	Agrawal and Tiwari [48]	Experimental and theoretical	Energy–economic analysis	33.54	7.13	NA	NA
2010	Sarhaddi et al. [14]	Experimental and theoretical	Energy analysis	17.18	10	45	NA
2010	Sarhaddi et al. [15]	Experimental and theoretical	Energy–exergy analysis	17.18	10	45	10.75
2010	Shahsavar and Ameri [49]	Experimental and theoretical	Energy analysis	60	9.5	72	NA
2011	Agrawal and Tiwari [50]	Theoretical	Energy–exergy analysis	70.62	NA	NA	NA
2012	Amori and Al-Najjar [51]	Theoretical	Energy analysis	19.4-22.8	9-12.3	47.8-53.6	NA
2012	Agrawal et al. [52]	Experimental and theoretical	Energy–exergy analysis	35.7	12.4	NA	NA
2013	Agrawal and Tiwari [53]	Experimental	Energy–exergy–environmental analysis	32	NA	NA	NA

Table 1. Performance of air-based PVT systems *(continued)*

2014	Yang and Athienitis [24]	Experimental and theoretical	Energy analysis	27.1	10	NA	NA
2014	Kim et al. [54]	Experimental	Energy analysis	22	15	NA	NA
2015	Li et al. [56]	Experimental and theoretical	Energy analysis	50	11.9-12.4	77.7	NA
2015	Good et al. [57]	Experimental	Energy analysis	71.5	17.4	NA	NA
2015	Ahn et al. [58]	Experimental	Energy analysis	23	15	38	NA
2015	Jahromi et al. [59]	Theoretical	Energy–exergy–economic analysis	51.6-52	7.5-8.7	NA	9.6-9.7
2015	Kamel and Fung [60]	Theoretical	Energy analysis	32.8-41	16-17	NA	NA
2015	Rajoria et al. [61]	Theoretical	Energy–exergy–enviro-economic analysis	12.1-28.1	3.1-9.1	NA	NA
2016	Gholampour and Ameri [62]	Experimental	Energy–exergy analysis	55	NA	69.91	8.66
2016	Rounis et al. [63]	Theoretical	Energy analysis	48	16.5	NA	NA
2016	Mojumder et al. [64]	Experimental and theoretical	Energy analysis	56.19	13.75	NA	NA
2016	Hazami et al. [65]	Experimental and theoretical	Energy–exergy analysis	50	15	NA	14.8
2017	Salem et al. [67]	Experimental	Energy–exergy analysis	31.6-57.9	17.7-38.4	59.3-92	11.1-13.5
2018	Fudholi et al. [10]	Experimental and theoretical	Energy–exergy analysis	21.3-82.9	9.87-11.34	31.21-94.24	12.66-12.91

5. CONCLUSIONS

PVT systems combine solar energy and PV collectors, which simultaneously produce heat and electrical energy. The efficiency and energy products from the combination of PV panels and collectors are higher than that of a separated system. Researchers and companies have proposed various designs to improve the overall efficiency of PVT systems. However, the lack of information on the commercial viability and long-term performance of a PVT system decreases its acceptance by the market.

Researchers have developed mathematical models to evaluate the performance of PVT systems with different collector designs. Energy balance is the basic concept in developing the mathematical models at a steady state. The performance of PVT systems is influenced by mass flow rates, collector geometry and other parameters. Model confirmation has been conducted to examine the behaviour of an actual system. To confirm the mathematical model, researchers have assessed either experimental or analytical results. Theoretical and experimental results have been generally consistent when the correct mathematical model is employed. Various approaches are limited because the precision of several key parameters is low and mistakes often occur in obtaining experimental results due to carelessness.

ACKNOWLEDGEMENTS

We gratefully acknowledge the funding from USAID through the SHERA program-Centre for Development of Sustainable Region (CDSR). In year 2017-2021 CDSR is led by Center for Energy Studies-UGM

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BIOGRAPHIES OF AUTHORS

Ahmad Fudholi, Ph.D, M.Sc obtained his S.Si (2002) in physics. He was born in 1980 in Pekanbaru, Indonesia. He served as was the Head of the Physics Department at Rab University Pekanbaru, Riau, Indonesia, for four years (2004–2008). A. Fudholi started his master course in Energy Technology (2005–2007) at Universiti Kebangsaan Malaysia (UKM). After obtaining his Master's, he became a research assistant at UKM until. After his Ph. D (2012) in renewable energy, he became postdoctoral in the Solar Energy Research Institute (SERI) UKM until 2013. He joined the SERI as a lecturer in 2014. He received more than USD 400,000 worth of research grant (16 grant/project) in 2014–2018. He supervised and completed more than 30 M. Sc projects. To date, he has managed to supervise nine Ph. D (seven as main supervisors and two as co-supervisor), one Master's student by research mode and one Master's student by coursework mode. He was also an examiner (five Ph. D and one M. Sc). His current research focus is renewable energy, particularly solar energy technology, micropower systems, solar drying systems and advanced solar thermal systems (solar-assisted drying, solar heat pumps, PVT systems). He has published more than 120 peer-reviewed papers, of which 37 papers are in the ISI index (more 25 Q1, impact factor more than 4) and more than 80 papers are in the Scopus index. He has published more than 80 papers in international conferences. He has a total citation of 1225 and a h-index of 17 in Scopus (Author ID: 57195432490). He has a total citation of 1684 and a h-index of 21 in Google Scholar. He has been appointed as reviewer of high-impact (Q1) journals. He has also been appointed as editor of journals. He has received several international awards. He has also been invited as speaker in the Workshop of Scientific Journal Writing; Writing Scientific Papers Steps Towards Successful Publish in High Impact (Q1) Journals. He owns one patent and two copyrights.

Muhammad Zohri, M.Sc REN obtained his S.Si (2009) in physics. Originally from Lombok, Indonesia, he graduated with M.Sc (2017) in Renewable Energi from Solar Energy Research Institute (SERI) UKM, Malaysia. He was appointed a Graduate Research Assistant (GRA) under Dr. Ahmad Fudholi. His M.Sc thesis was under the supervision of Dr. Ahmad Fudholi. His M.Sc dissertation was on the Performances of Photovoltaic-Thermal (PVT) with and without V-Collectors. He has published 10 Papers, which 7 Paper in Scopus Index with a h-index of 3. His current research focus is on solar energy technology. Currently, he is a PhD candidate under the main supervision of Dr. Ahmad Fudholi at the SERI in Universiti Kebangsaan Malaysia.

Ivan Taslim, S.Si, M.T from South Sulawesi, Indonesia. He graduated with the M.T in Geology Engineering from University of Hasanuddin in 2014. In 2015, he joined as lecturer at the Department of Geography, Faculty of Science and Technology, University of Muhammadiyah Gorontalo. His main areas of research interest are Management Risk Disaster, Geospatial Data Science and Climate Change with no limited to Renewable Energy. He is currently one of the researchers from USAID SHERA who focuses on developing and using renewable energy in Indonesia. Currently, he is entrusted to work with the Gorontalo Regional Government as a staff in the field of Climate Change and Disaster Mitigation.

Merita Ayu Indrianti, S.P., M.P from Banjarmasin South Borneo, Indonesia. She graduated in Agriculture from University of Hasanuddin in 2016. She has working as a lecturer at the Department of Agriculture University of Muhammadiyah Gorontalo since 2014. Her main areas of research interest are Socio-Economic in Agriculture, Biomass and Biogas energy and Integrated Farming System for Food Security. In her career, she had served as secretary of the Agricultural Study Center (2015) and secretary of the Agribusiness study program (2016) in Department of Agriculture.

Intan Noviantari Manyoe, S.Si, M.T from Gorontalo, Indonesia. She was born in 1982, and graduate from University of Hasanuddin with a degree in Geophysics and have a masters in Geology Engineering in 2014. She is working as a lecture at the Department of Geology also Head of Geology Engineering Laboratory at University State of Gorontalo. Her main areas of research interest are Geophysics, Tectonic, Volcano and Geothermal.