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Original Article

Integrated Solar Photovoltaic-Thermal, Solar Desalination, and Organic Rankine Cycle System for Sustainable Energy and Water Production

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Abstract *- The increasing global demand for both clean energy and freshwater has driven the development of integrated renewable systems capable of addressing both challenges simultaneously. This paper presents a comprehensive review and conceptual design of a hybrid system combining solar Photovoltaic-Thermal (PVT) collectors, solar desalination technologies, and the Organic Rankine Cycle (ORC). The PVT system simultaneously generates electricity and thermal energy, which is utilized to drive desalination processes and power an ORC for additional electricity generation. Integration enhances overall system efficiency, reduces energy waste, and improves economic feasibility. The main objective of this paper is to present a mathematical and numerical modelling of the use of nanofluids and PV-thermal solar to power the multistage flashing chamber thermal process. The model proposed has been established after the mass and energy conservation equations of the flashing process integrated with the vapor and nanofluids thermal and thermophysical properties at different volume fractions, as well as solar radiation. The study examines system configurations, thermodynamic performance, and key operational parameters, highlighting the potential of such hybrid systems in arid and remote regions.*

Keywords - *PV-Thermal, Solar Desalination, ORC, Modeling, Simulation, Validation.*

1. Introduction

Water scarcity and energy demand are two of the most pressing global challenges. Conventional desalination technologies such as reverse osmosis are energy-intensive and often rely on fossil fuels. Solar energy offers a sustainable alternative, particularly in regions with high solar irradiance.

Solar Photovoltaic-Thermal (PVT) systems improve solar utilization by combining electrical and thermal energy generation. When integrated with desalination and power cycles such as the Organic Rankine Cycle (ORC), these systems can: maximize solar energy, utilize, provide simultaneous electricity and freshwater, and improve overall system efficiency.

2. Major Research Gaps

1. Most studies optimize individual subsystems rather than the complete system.
2. Insufficient utilization of PV-T waste heat
3. Limited research on thermal cascading
4. Energy analysis is often emphasized over exergy analysis
5. Lack of multi-objective optimization
6. Dynamic solar conditions are insufficiently addressed
7. Thermal energy storage is not sufficiently integrated
8. Desalination technology selection
9. Lack of comprehensive economic optimization
10. Environmental impact needs an integrated assessment

However, energy and financial requirements limit how widely that process can be used. We believe that solar energy is the logical response to these limitations and can power thermal and electrical desalination systems. It was shown by references [1 through 19] that solar desalination can be achieved, particularly in areas where solar intensity is high and there is a lack of fresh drinking water. Therefore, this research has been undertaken to study the impact of solar energy and nanofluids on the desalination process.

An integrated system that uses a flashing desalination technique coupled with a nano-fluid-based solar collector as a heat source has been presented by reference [12] to study both the effect of different operating modes and that of the variation of functioning parameters and weather conditions on the freshwater production using nanofluid. The flashing unit is performed by a similar construction design technique to a

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commercial Multi-Stage Flashing (MSF) plant. Another objective of the reported mathematical model was to calculate the productivity of the system under different operating conditions.

Nannaronea et al. 6 presented a general model to simulate the Multiple Stage Flash distillation, MSF process. The model was implemented within the Camel-ProTM Process Simulator. Several validation tests were conducted to confirm that the model is an efficient tool for MSF plant design and prediction of the most important variables in the MSF process. Lumped parameter dynamic models were developed in Al-Fulaij Ph D thesis [7] for the once-through (MSF-OT) and the brine circulation (MSF-BC) processes.

The models were coded using the PROMS modelling program. The model predictions for both MSF-OT and MSF-BC in steady state and dynamic conditions showed good agreement against data from existing MSF plants with an error of less than 1.5%. Reference [9] proposed methodology provides a set of modular simulations of components that allow the creation of complex models used in optimization of the full water desalination supply chain.

The optimization scheme included Mathematical Programming (MP) models that are solved by an external MP solver for Saudi Arabia, which is considered the worldwide leader in desalinated water capacity.

A mathematical model for a Multistage Flash (MSF) desalination system with Brine Recirculation (BR) configuration has been developed and presented by reference [13]. The heat source for BR-MSF was chosen as a nanofluid-based Direct Absorption Solar Collector (DASC), where the numerical model was developed. Both these systems, BR-MSF and DASC, were coupled via a counter-current flow heat exchanger.

The overall performance of the combined system was determined in terms of the Gained Output Ratio, referred to as (GOR). The conceptual design for a Photovoltaic Thermal (PV/T) solar panel has been developed and analyzed to control the inherent temperature increase of PV cells to increase electrical efficiency [14-17]. A hybrid solar panel has been developed and presented by Yang et al. [12] and Sami [16,17,19] to integrate Photovoltaic (PV) cells onto a substrate through a Functionally Graded Material (FGM) with water tubes cast inside, through which water serves as both a heat sink and solar heat collector.

Further to the literature review, it is evident that very limited research work has been published on the use of nanofluids in the desalination process and using Multistage Flashing (MSF) chamber process modeling and simulation of seawater brine. Thermal and membrane desalination were focused on the evaporation processes using steam. The novel concept presented in this paper for the MSF implements PV-Thermal solar panels using hot heat transfer fluid with nanofluids in the MSF process integrated with the Organic Rankine Cycle to generate power needed for a self-sufficient hybrid desalination system, as shown in Figures 1 and 2.

3. Strongest Novelty Opportunity

The most compelling novelty would be to develop an AI-Optimized Solar PV-T–ORC–Desalination Integrated Energy-Water System. Rather than simply connecting three technologies, the research would develop an intelligent controller that determines in real time:

- PV-T operating temperature,
- coolant flow rate,
- ORC working-fluid flow rate,
- ORC evaporation pressure,
- ORC condensation pressure,
- heat allocation,
- desalination feed flow,
- storage charging/discharging,
- freshwater production rate.

The novelty of this research lies in the development of an integrated solar photovoltaic-thermal (PV-T), Organic Rankine Cycle (ORC), and solar desalination system capable of simultaneous electricity and freshwater production through multi-stage thermal-energy utilization.

Unlike conventional studies that investigate PV-T collectors, ORC systems, and desalination technologies independently or through simple thermal coupling, the proposed system establishes a cascading thermal-energy pathway in which heat recovered from the PV-T collector is first utilized for power generation through the ORC and subsequently recovered for desalination and feedwater preheating.

A second major contribution is the development of a thermodynamic and exergy-based framework for identifying optimum heat allocation among electricity generation, desalination, and thermal storage.

The system is further coupled with artificial-intelligence-based multi-objective optimization to maximize net electrical output, freshwater production, and overall exergy efficiency while minimizing exergy destruction, levelized cost of electricity, levelized cost of water, and carbon emissions.

The proposed approach, therefore, transforms the conventional solar-energy system from a single-output electricity generator into an integrated energy-water cogeneration platform. The research provides a unified framework for evaluating the thermodynamic, economic, environmental, and operational performance of the integrated system under variable solar-resource conditions. This

approach has the potential to establish a new pathway for sustainable electricity and freshwater production in water-stressed regions and remote communities.

The main objective of this paper is to present a mathematical and numerical modelling of the use of nanofluids and PV-thermal solar to power the multistage flashing chamber thermal process. The model proposed has been established after the mass and energy conservation equations of the flashing process integrated with the vapor and nanofluids thermal and thermophysical properties at different volume fractions, as well as solar radiation.

The nanofluids studied are Al_2O_3, CuO, Fe304, and SiO_2 at different volume fractions; however, only the results of the nanofluid are presented. Al2O3 is presented hereby. Other publications on the subject matter will follow.

The process of multistage flashing using the PV-Thermal solar panels and nanofluids has been analyzed under different conditions of seawater (brine) salt concentration, brine flows, and temperatures, and nanofluids concentration, as well as solar radiation.

4. Numerical Modeling

4.1. PV Model

The solar photovoltaic panel is constructed of various modules, and each module consists of arrays and cells. The dynamic current output can be obtained as per references [13-15];

The AC power of the inverter output P(t) is calculated using the inverter efficiency. η_{inv} , output voltage between phases, neutral V_{fn}, and for single-phase current I_o and $cos\varphi$ as follows;

$$P(t) = \sqrt{3}\,\eta_{inv} V_{fn} I_o\, cos\varphi \qquad (1)$$

4.2. PV-Thermal Model

It is assumed in this model that all PV cells behave the same; therefore, this model can be applied to the whole PV solar panel. This model is an extension of the work presented by Sami and Campoverde [14], which states that the thermal heat absorbed by the PV solar cell can be calculated by the following equation;

$$Q_{in} = \alpha_{abs} G S_p \qquad (2)$$

Where;
α_{abs}: Overall absorption coefficient
G: Total Solar radiation incident on the PV module
S_p: Total area of the PV module

Meanwhile, the PV cell Temperature is computed from the following heat balance as per Sami and Martin [15];

$$mC_{p_module} \frac{dT_C}{dt} = Q_{in} - Q_{conv} - Q_{elect} \qquad (3)$$

Where;
T_C: PV Cell Temperature
mC_{p_module}: Thermal capacity of the PV module
t: time
Q_{in}: Energy received due to solar irradiation,
Q_{conv}: Energy loss due to Convection
Q_{elect}: Electrical power generated

Interested readers in the detailed calculations of the terms of the above equation are advised to consult references [14, 16].

4.3. Multistage Flashing Chamber Model

In this section, we present mathematical and numerical modelling of the use of nanofluids and PV-thermal solar to power the Multistage Flashing chamber thermal (MSF) process, as shown in Figure.1.

In this figure, the brine is preheated by the nanofluid circulating in the PV-thermal loop, where the dissipated heat from the PV solar panel is absorbed, as shown in the figure.

The flashing process occurs in the flashing chamber, where the flashed vapor is generated and condensed on the heat exchanger cooled down by the incoming brine flow. The distilled condensed vapor is collected, and the brine flow is circulated to the next flashing chamber, where the same flashing process is repeated.

The model proposed has been established after the mass and energy equations coupled with the state equations for the nanofluids and water as base fluid at different solar radiations.

This numerical process has been repeated for each of the flashing chambers. In the following, we present the mass and energy equations of the flow in the flashing chamber.

A PVT system integrates photovoltaic cells with a thermal collector. Cooling the PV panel improves electrical efficiency while capturing useful heat.

4.4. Performance Benefits

- Electrical efficiency increases due to temperature control
- Recovering thermal energy improves overall efficiency
- Typical combined efficiency: 60–80%

4.5. Role in Hybrid System

The PVT system serves as the primary energy source, supplying:

- Electricity for pumps and control systems
- Heat for desalination and ORC

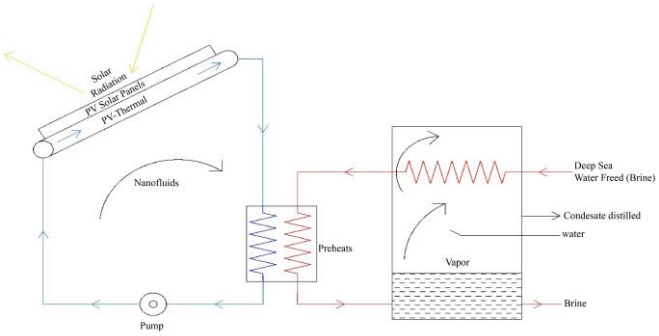

Fig. 1 PV-Thermal integrated Flashing Chamber process

Each flashing chamber is considered as a discrete control volume and has a constant volume; therefore, by applying the first law of thermodynamics to the control volume, the mass balance and energy balance across the flashing chamber can be given by the following equations, respectively [21];

$$\Sigma m_{in} - \Sigma m_{out} = 0 \quad (4)$$

$$\Sigma e_{in} - \Sigma e_{out} = 0 \quad (5)$$

Where m and e are the mass and energy entering and leaving the flashing chamber control volume?

The brine seawater mass balance across the preheater is;

$$m_{Bi} - m_{Bo} = 0 \quad (6)$$

Where m_{CBi} and m_{Bo} are the brine mass flow entering and leaving the preheater, respectively.

The brine concentration entering and leaving is given by the mass balance equation.

$$m_{Bi}S_{Bi} - m_{Bo}S_{Bo} = 0 \quad (7)$$

The distilled condensed mass balance is;

$$m_{Co} - m_{Ci} - m_{Dbrine} = 0 \quad (8)$$

Where, m_{Dbrine} It is the distilled mass of vapor condensed as per the Figure.1

The preheater energy balance is;

$$(m_{Dbrine} + \gamma m_{Bi})\Delta H_{evap} - m_{Bi}Cp_{brine}(T_{CBo} - T_{CBi}) = 0 \quad (9)$$

Where the distillate flashing fractionγ;

$$\gamma = \frac{Cp_{cond} * DT_{Stage}}{\Delta H_{evap}} \quad (10)$$

Where, DT_{Stage} and ΔH_{evap} These are the stage temperature difference and heat of evaporation, respectively.

4.6. Nanofluid Heat Transfer Fluid

Different equations have been reported in references [16-18] on the calculation of the specific heat, thermal conductivity, viscosity, and density using the law of mixtures. The thermophysical, thermodynamic, and heat transfer properties of nanofluids are determined in terms of the volumetric concentration of the nanoparticles as per the following equation;

$$\alpha_{total} = \alpha_{particles} + \alpha_{base\ fluid} \quad (11)$$

Where α represents the thermophysical property of a particular nanofluid.

The nanofluid thermal and thermophysical properties, α_{total} , can be calculated as follows;

$$\alpha_{total} = \alpha_{base\ fluid} + \alpha_{particles}.(\Phi) \quad (12)$$

Where, Φ represents the nano particles volumetric concentration.

The thermal conductivity, thermal diffusivity, and density of the nanofluids are related as follows [16-18];

$$\lambda = \alpha\ \delta\ C_p \quad (13)$$

Where Cp is the specific heat, α is the thermal diffusivity, ʎ and ρ represent the thermal conductivity and density, respectively.

Interested readers in further details about the calculations of the nanofluids' thermophysical and thermodynamic properties are advised to consult references [16-18, 19-21]. These references discuss the impact of the nanofluid concentrations on the thermophysical properties of the said nanofluids. Moreover, the scope of this study is to discuss the MSF process using the PV-Thermal with nanofluids as heat transfer fluids and not to discuss the thermophysical properties of the nanofluids since they are discussed elsewhere; references [16-18, 19-21].

Finally, the Availability and Irreversibility of the flashing process are discussed in the following;

$$A_q = \Sigma(1 - T_{amb}/T_J)\ Q_J \quad (14)$$

Where A_q is the flow availability change under steady state conditions per stage, and is the availability transfer due to Q_J, the heat transfer between the control volume and its surroundings. T_{amb} *and* T_j are the ambient temperature and the flashing chamber temperature, respectively.

The destruction of availability, i.e., irreversibility in the process per stage, can be determined from the following;

$$I_j = T_{amb}\ x\ S_J \quad (15)$$

Where the S_j represents the entropy of the flashing process at each stage.

4.7. ORC Model

The ORC converts low-to-medium temperature heat into electricity using an organic working fluid. An Organic Rankine Cycle (ORC) turns low-temperature heat into electricity by using a special fluid that boils at a very low temperature. In the current study, a special refrigerant mixture is used that has a low boiling point temperature. Interested readers in the subject matter should consult Sami [21].

The cycle includes the following components, as shown in Figure 2:

1. Pump
2. Evaporator
3. Turbine
4. Condenser

The energy balance at the ORC cycle gives the following [6,7,10]:

$$W_{ORC} = m_{ref}(h_1 - h_2) \quad (16)$$

$$Q_{WHB} = m_{ref}(h_1 - h_4) \quad (17)$$

$$Q_{Cond} = m_r\ Qcond = m_{ef}(h_2 - h_3) \quad (18)$$

$$W_{pORC} = m_{ref}(h_4 - h_3) \quad (19)$$

$$Q_{Cc} = m_{ref}(h_6 - h_5) \quad (20)$$

$$Q_{reg} = m_{ref}(h_7 - h_6) \quad (21)$$

where h is the enthalpy
h_1: enthalpy at the outlet of the waste heat boiler (KJ/Kg)
h_2: enthalpy at the exit of the vapor turbine (KJ/Kg)
h_3: enthalpy at the condenser outlet (kJ/kg)
h_4: enthalpy at ORC pump outlet (kJ/kg)
h_5: enthalpy at the inlet of cooling/freezing coil (kj/kg)
h_6: enthalpy at the outlet of cooling/freezing coil (kj/kg)
h_7: enthalpy at the outlet of the regenerator (kJ/Kg)
m_{ref}: refrigerant mass flow rate (kg/s)

The ORC-PV hybrid system efficiency can be calculated as

$$\eta_{ORC-h} = \frac{W_{ORC} + p(t) + Qcc - W_{P_{ORC}}}{Q_{in}} \quad (22)$$

where
W_{ORC}: power produced by ORC (KW)
$p(t)$: PV solar output (kW)
Qcc: cooling coil thermal capacity (kW)
$W_{P_{ORC}}$: pump power consumption
Q_{in}: solar radiation (kW)

4.8. Magnetized Nanofluids

Equations (11) through (15) can be used to determine other thermophysical properties, such as α, the thermal diffusivity, ʎ, and ρ, which represent the thermal conductivity and density as different magnetic forces Gauss published in the literature properties ([4] through [6]) as a function of the properties outlined in the Table.1

Table 1. Thermophysical Properties of magnetized nanofluids

	$Ai_2 0_3$	CuO	Fe304	SiO_2
$C_{p\,nf}$	b = 0.1042a + 6226.5	b = 0.2011a + 5730.8	b= 0.8318a + 4269.8	b = 0.6187a + 4293.2
K_{nf}	b = 2E-05a + 1.4888	b = 5E-05a + 1.3703	b= 0.0002a + 1.0209	b = 0.0001a + 1.0265
h	b = 0.0031a + 73.092	b = 0.0031a + 73.073	b = 0.003a + 73.225	b = 0.003a + 73.231

Where "b" represents the nanofluid-specific property and "a" is the magnetic field force in Gauss. C_{pnf}, Knf, and h are the specific heat, thermal conductivity, and heat transfer coefficients of nanofluids.

The use of magnetically responsive Fe_3O_4 nanofluids provides an actively controllable heat-transfer mechanism for the PV-T collector, enabling dynamic regulation of PV temperature and thermal-energy recovery. When coupled with an ORC and solar desalination subsystem, the magnetized nanofluid can facilitate thermal cascading from high-grade PV-T heat to electricity generation and subsequently to freshwater production. AI-based multi-objective optimization can then determine the optimum magnetic-field intensity, nanoparticle concentration, and flow conditions while accounting for heat-transfer enhancement, pumping power, magnetic-field energy consumption, exergy destruction, electricity production, and freshwater yield.

Thereafter, we use magnetized nanofluids because they potentially provide higher and, more importantly, actively controllable heat transfer—allowing the PV-T system to operate at a lower PV temperature while maximizing the useful heat available for ORC electricity generation and desalination.

4.9. Energy Flow Mechanism and Role in Hybrid System

The Energy flow diagram and process are shown in Figures 1 and 2. The process is described as follows;

- Solar radiation is absorbed by the PVT collector
- Electricity is generated by photovoltaic cells
- Heat is extracted by a working fluid
- Thermal energy is directed to:
  - Desalination unit (primary use)
  - ORC evaporator (secondary use)

This cascading use of energy ensures minimal thermal losses.

ORC efficiency depends on:

- Heat source temperature
- Working fluid properties
- System design

4.10. Overall Energy Efficiency

$$\eta_{total} = \eta_{PV} + \eta_{thermal} + \eta_{ORC} \quad (23)$$

Where:

- η_{PV}: Electrical efficiency of PV cells
- $\eta_{thermal}$: Thermal efficiency used for desalination
- η_{ORC}: ORC conversion efficiency

4.11. Energy Cascade Utilization

The system uses a cascading approach:

1. High-grade energy is used to generate electricity using PV solar panel collectors/
2. Medium-grade heat is utilized to drive flash desalination chambers using PV-Thermal solar collectors.
3. Low-grade heat is a byproduct that drives the waste heat boiler at the Organic Rankine Cycle ORC to ensure the proposed system is self-powered.

The proposed system offers the following benefits:

- Dual production: electricity and freshwater
- High efficiency due to energy cascading
- Reduced Environmental Impact
- Energy independence in remote areas
- Scalability from small communities to industrial use

5. Numerical Procedure

The energy conversion process in the PV-Th panels, integrated ORC, and cooling described by Equations (1)–(23) and presented in Figures 1 and 2 was programmed and solved numerically. The calculation starts with the input of the parameters of the PV-Thermal solar panel, thermal tubes, and characteristics of the nanoparticles: Al_2O_3, CuO, Fe_3O_4, and SiO_2, and water as the heat transfer fluid. The system equations were integrated into the finite-difference formulations to determine the behavior of the process shown in Figure 1. Iterations were performed using MATLAB iteration techniques until a converged solution was reached with less than 0.05. With the known values of solar radiation, the mass flow rate of the nanofluid circulating in the thin tubes welded to the PV solar collector was determined.

Then, the thermophysical properties and the heat transfer characteristics of the base fluid, water, and nanofluids at different concentrations were determined. Then, the parameters describing the behavior of PV-Thermal solar panels, ORC, and the cooling coil were determined under different conditions. Finally, the hybrid system efficiencies were calculated.

6. Discussion and Analysis

The system of Equations (1)–(23) has been numerically solved in finite-difference formulation for the energy conversion process in the hybrid system of PV-Thermal solar collector, ORC with cooling capability employing nanofluids: Al_2O_3, CuO, Fe_3O_4, and SiO_2 at different concentrations and water as base heat transfer fluid. In the following sections, the predicted results are presented under different inlet conditions, such as solar insolation, heat transfer fluid flow rates from the PV-Thermal, heat transfer fluid temperatures, and various nanofluids at different volumetric concentrations. In the numerical simulation, 100 PV solar panels were assumed with 300 watts per PV solar panel. Solar radiation was taken as 500, 750, 1000, and finally, 1200 w/m^2, and the heat transfer fluid temperature varied from 176 °F to 212 °F. As reported in Sami and Marin [15], the efficiency of the PV solar panels used in this study varies between 19% and 23% depending on the solar radiation. These values will be taken and considered as base values for comparison between the hybrid system efficiency of the PV-Thermal and ORC system and that of the PV solar panels.

The heat transfer fluid flow rate circulates in the loop, driving the heat boiler of the ORC between 8.89 GPM (4208 lb/hr) and 22.6 GPM (10550 lb/hr) at temperatures varying between 176 °F and 212 °F. For comparison purposes, the pressure in the refrigerant mixture cycle of the ORC was kept constant between the waste heat boiler and the condenser at 133 psi and 55 psi, respectively. The boiling temperature of the refrigerant mixture was at –28 °F. The refrigerant mixture exits the waste heat boiler to the vapor turbine at vapor saturation conditions. Appropriate heat exchanger and vapor turbine efficiency values were used for the ORC cycle. The Carnot cycle efficiency of the ORC conditions was 27.38%, and on average, the ORC efficiency was 8.3% using the environmentally sound quaternary refrigerant mixture composed of R152a, R245fa, R125, and R1234fy. In the following sections, the impact of solar radiation on the Hybrid system performance and the efficiency of the hybrid system composed of the PV solar panel, PV-Thermal, and the ORC, as calculated by Equation (22), are analyzed and discussed.

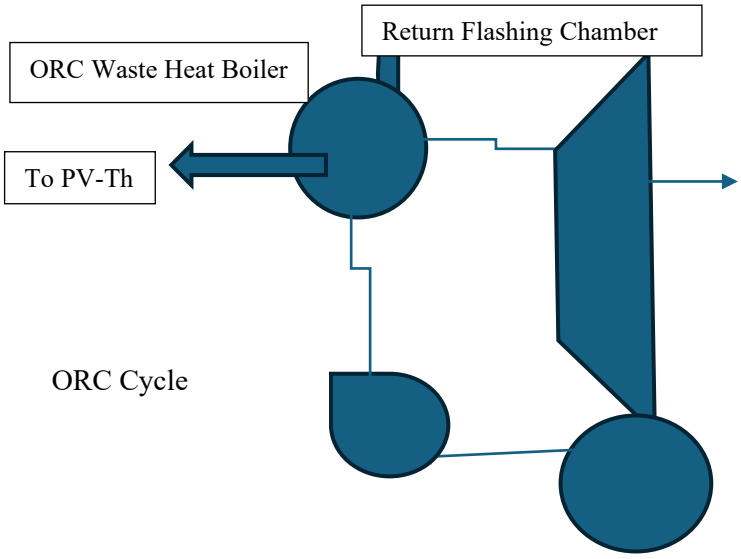

Fig. 2 PV-Thermal integrated Flashing Chamber and ORC process

Since nanofluid Ai2O3 is one of the most common nanofluids studied and reported in the literature, Figures 3 through 6 have been constructed to demonstrate the impact of using this nanofluid at concentrations 10% and 20% on the different behavior of the most important key parameters of the flashing process and also compared to water as base fluid, at different solar radiations; ranging between 500 to 1200 W/m^2, respectively. When a magnetic field is applied to the magnetized nanofluid, and there is a temperature gradient (temperature difference) within the fluid, the aligned magnetic particles can induce fluid flow through a phenomenon called magnetohydrodynamic convection. This induced flow can significantly enhance heat transfer by promoting mixing and convective heat exchange within the fluid. Examining the results presented in Figures 3 and 4, these suggest that the higher the nanofluid concentration as a heat transfer fluid, the lower the salt % in the flashed flow leaving the set of flashing chambers compared to water as a base heat transfer fluid used in the brine preheater. On the other hand, it can be seen from the figures that the higher the solar radiation, the lower the salt % in the flashed flow. This can be attributed to the fact that higher solar radiation results in higher temperature of the heat transfer fluid and the brine flow in the preheater entering the flashing chambers. Also, the higher the heat transfer fluid temperatures, the higher the brine flow temperatures, and the higher the amount of distilled water evaporated or flashed. It can also be noticed from the results that the salt % in brine is increased progressively in the flashing chambers until it reaches its maximum value at the final chamber.

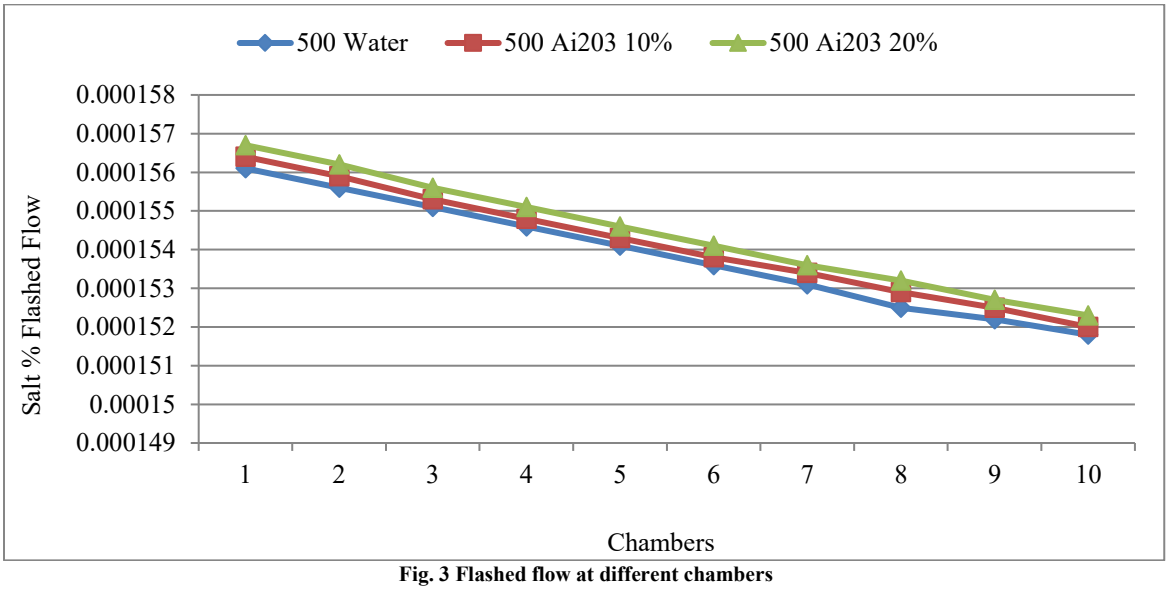

Fig. 3 Flashed flow at different chambers

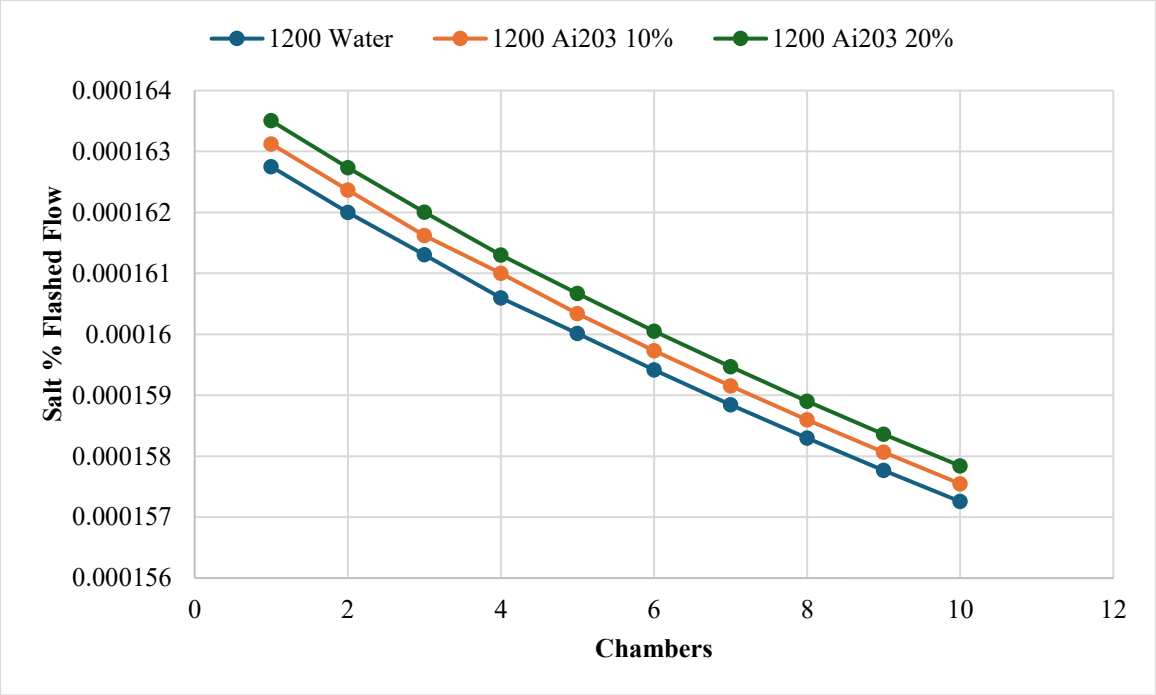

Fig. 4 Flashed flow at different chambers

Figures 5 and 6 display the changes in the flashed flow at each flashing chamber, at different solar radiation, where the flashed flow is reduced progressively and reaches its lowest value at the last flashing chamber. The amount of the produced distillate decreases along the stages and consequently along flash temperature and pressure decreasing profiles. This is due to the increase in the heat of vaporization at lower saturation temperatures, and therefore, a smaller amount of vapor is extracted from brine. Factually, the data in these figures show that the higher the solar radiation the temperature is, the more the distillation rate rises, since a larger amount of vapor can be extracted from saltwater. The results also show that the higher the solar radiation, the higher the flashed flow per chamber. In addition, the results also demonstrate that the higher the nanofluid AI2O3 concentration, the higher the flashed flow produced during the flashing process compared to water as a base fluid.

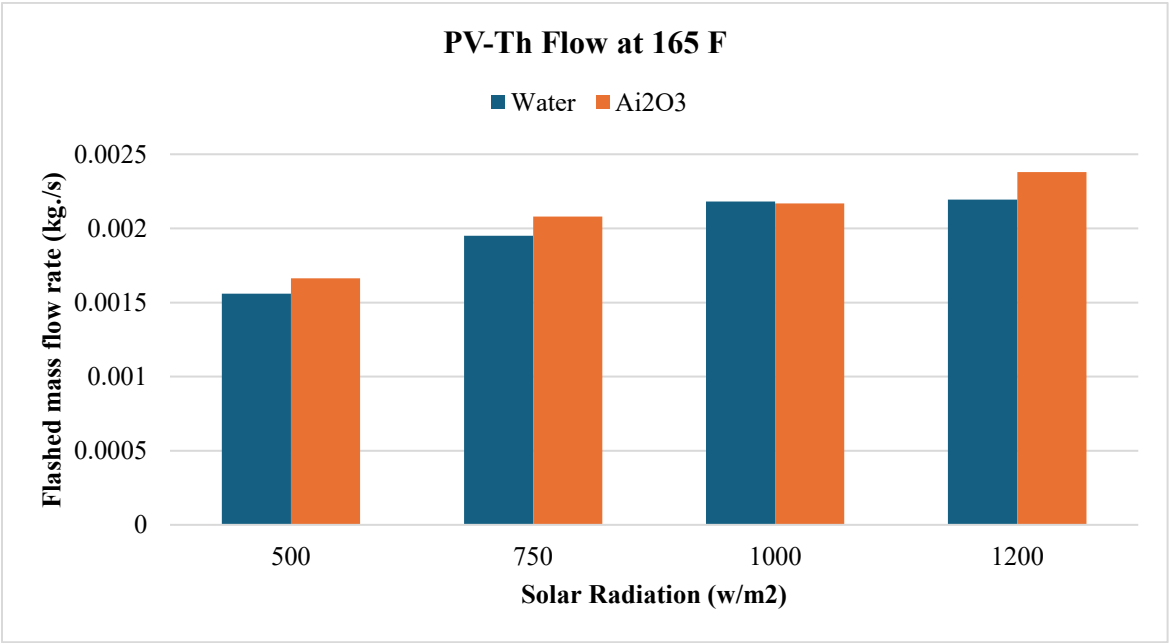

Fig. 5 Flashed flow at different chambers at different solar radiation levels.

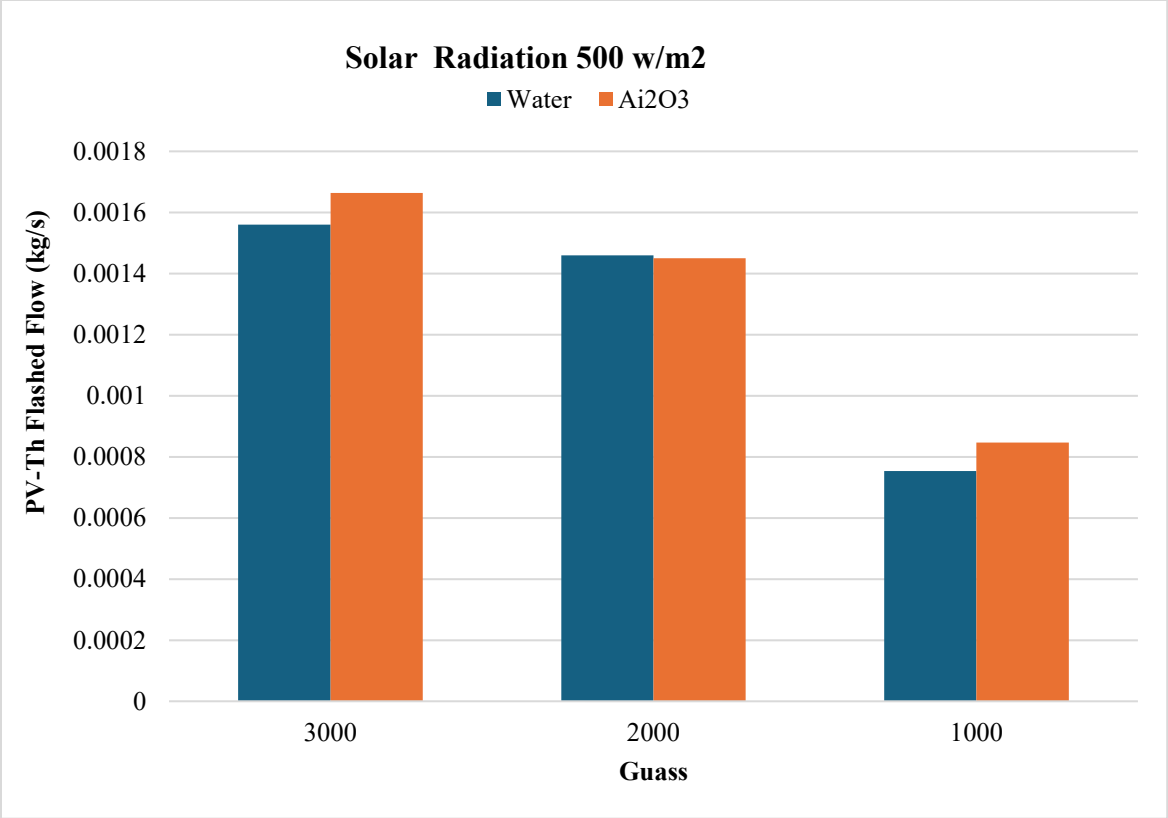

Fig. 6 Flashed flow at different chambers at different magnetic field levels.

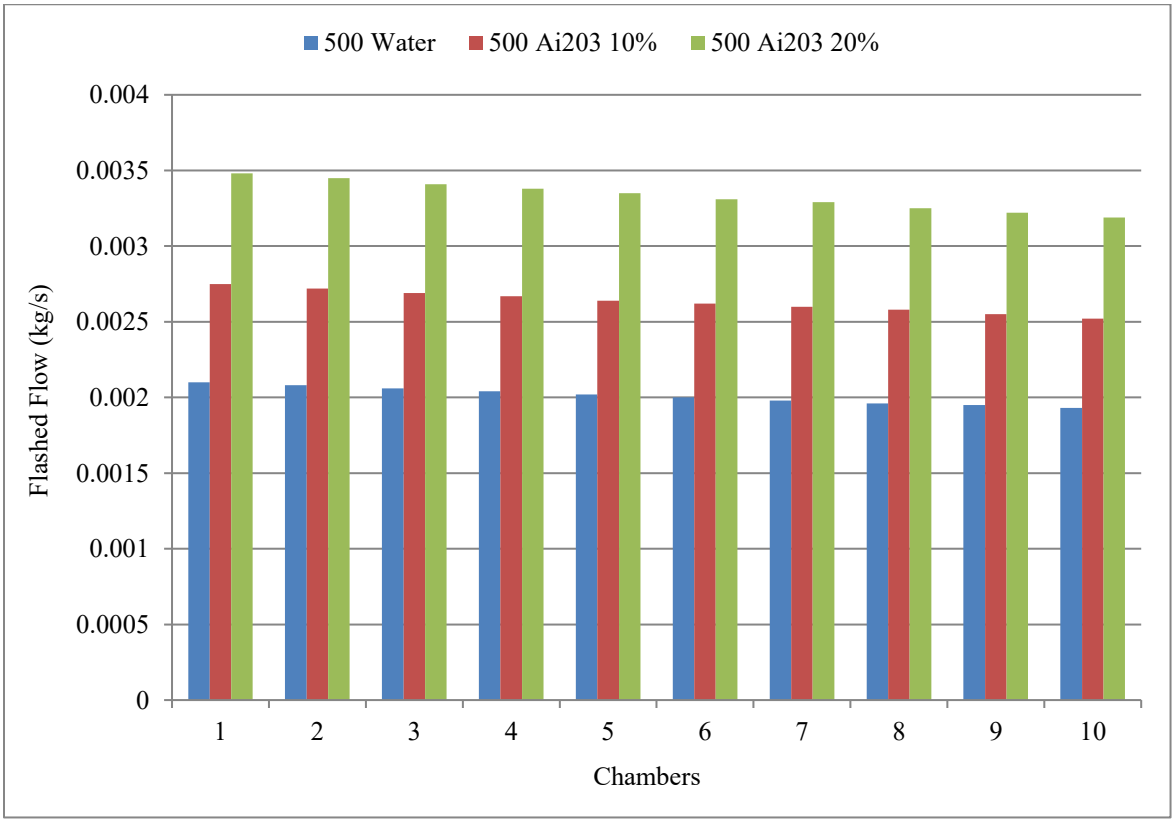

Fig. 7 Flashed flow at different chambers.

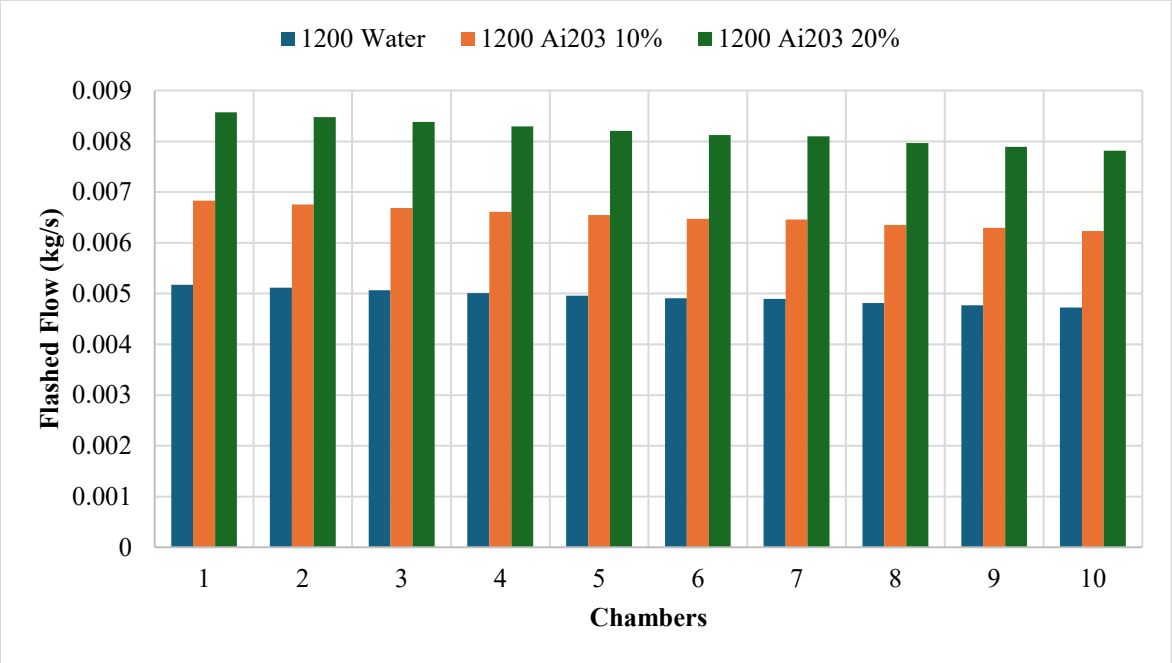

Fig. 8 Flashed flow at different chambers.

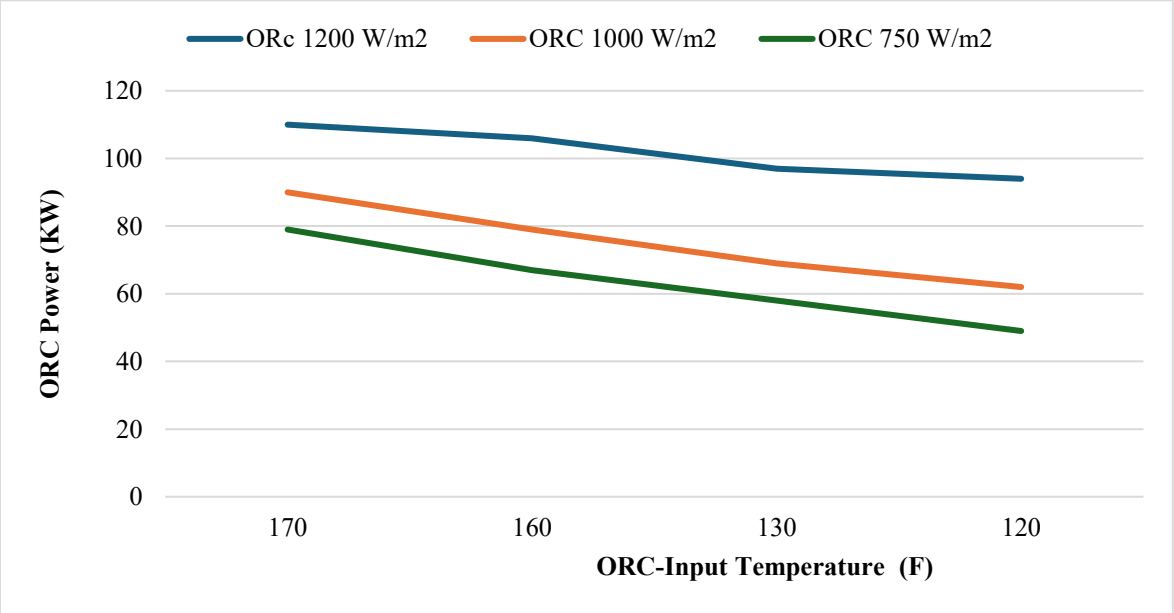

Fig. 9 ORC power produced at different Input temperatures

Equations (1) through (4) have been solved to predict the dynamic total power generated, efficiencies, and the key important parameters of a hybrid system composed of a novel combined concept of a photovoltaic-thermal solar panel hybrid system. As reported and discussed by Sami [13] through [15], it is evident that the dynamic PV-Thermal studies show that the higher the solar radiation, the higher the thermal and hybrid efficiencies. It is also observed that hybrid efficiency exhibits lower values than thermal efficiency since the PV solar panel efficiency is significantly lower than the thermal efficiency. Furthermore, the PV simulation study results reported in references [13] through [15] showed that the higher the solar radiation, the more accelerated the increase in the PV cell temperature. Consequently, it also shows that the higher the solar radiation, the higher the PV power and PV amperage.

Sami [13-15, 21-23] and others in the literature reported that nanofluids, such as CuO, Fe3O4, and SiO_2, have received significant attention in the literature in the PV-Thermal hybrid

system. It is evident from the findings of these references that the nanofluid CuO has the highest characteristic performance among the other nanofluids and water as a base heat transfer fluid in the PV-Thermal solar collector system. This can obviously be attributed to the higher thermodynamic, thermophysical, and heat transfer properties of the nanofluid CuO, which contribute to outperforming other nanofluids. Also, the references reported that the PV-Thermal efficiency is enhanced with higher concentrations of this nanofluid at constant solar radiation.

It has been reported by references [21] through [23] that an improvement in the heat transfer capacity becomes more significant with the increase in the volume concentration of the particle loading in nanofluids. This enhancement in the heat transfer capacity of the heat transfer fluid increases the thermal energy delivered to the waste heat boiler of the ORC and thus increases the power output of the ORC and ORC efficiency. Therefore, the results presented in the references and others show that the enhancement of the efficiency of the hybrid system in question is significantly dependent upon not only the solar radiation but also on the nanofluids concentration and the type of nanofluid, as well as the fluid flow temperature driving the ORC.

The new concept of the PV-Thermal integrated ORC cycle presented here includes an added feature that shows how the different parameters impact the ORC cycle. The results presented in Figure.9 demonstrate that the power generated by the ORC depends upon various parameters, such as solar radiation, the temperature of the heat transfer fluid, and the types of nanofluids and their concentrations. It is quite evident from the results presented in these figures and others obtained during this study with the different nanofluid concentrations that the higher the heat transfer fluid temperature, the higher the ORC power produced. As discussed elsewhere in this paper, in the case of hybrid system efficiency, it is believed that the enhancement of the power generated is due to the higher thermo-physical properties of nanofluids.

It has been reported by Sami [15-19], Ali H.A. Al-Waelia et al. [17], as well as others, that transport properties such as the density, specific heat, heat capacity, viscosity, and thermal conductivity of nanofluids are functions of the nanofluids' concentrations and significantly impact the convective heat transfer of nanofluids [18].

In thermodynamics, changes in the state or process of a system cannot be restored to its initial state by changes in the properties of the system without the expenditure of energy [24]. An irreversible process increases the entropy of the system in question. The second law of thermodynamics can be used to determine the irreversibility of a process as per equation (16). In a thermodynamic process, the energy is lost to the surroundings in the form of Irreversible energy. However, the remaining amount of energy is defined as the Available Energy in the process [24].

This thermodynamic principle has been applied in the current study of the flashing chamber process and expressed in equations (14) and (15) to assess the lost and available energy. In particular, Figures 10 through 12 have been constructed to demonstrate the irreversibility and availability of solar radiation 1200 w/m2 during the flashing process at each stage.

The results displayed in these figures clearly show that irreversibility is significantly lower when nanofluid AI2O3 is used. It is slowly reduced in the last flashing chamber. The availability exhibits similar behavior but is progressively reduced in the last flashing chamber.

However, it has been reported by reference [21] and [23] that the irreversibility is reduced by using nanofluid AI2O3 at a higher concentration compared to water as a base fluid. Furthermore, the higher the concentration of AI2O3, the higher the availability at the last flashing chamber. However, the availability is progressively reduced at the last flashing chamber.

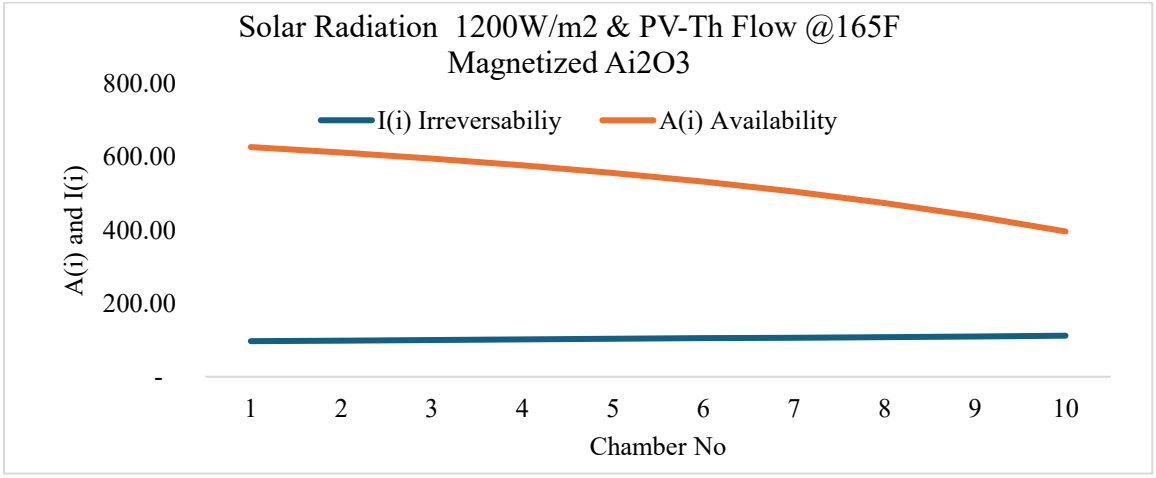

Fig. 10 Irreversibility and Availability

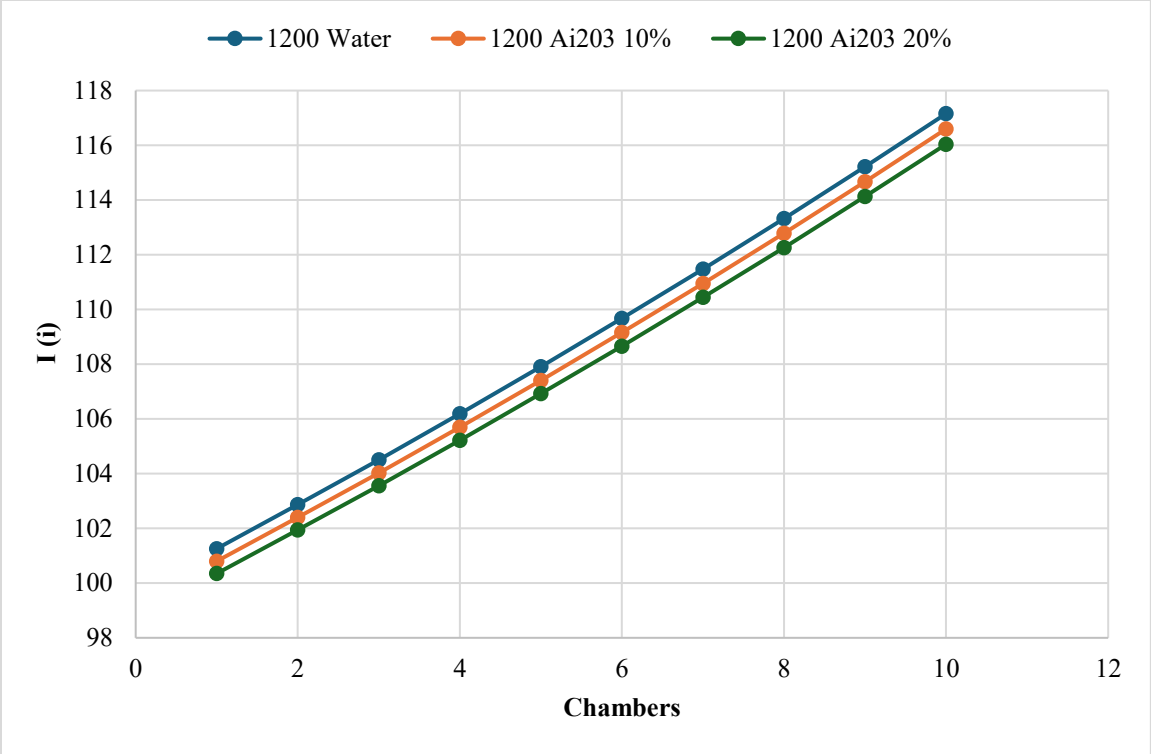

Fig. 11 Irreversibility at different flashing chambers

The hybrid efficiency of the PV-Thermal ORC system is determined by equation (23) and displayed in Figure 13 at different solar radiation. As reported [24], higher efficiencies were encountered with the magnetized nanofluids compared to the other fluids, such as water.

This is quite expected as with the nanofluid AiO203, more thermal energy is transferred to the refrigerant mixture in the waste heat boiler, resulting in higher refrigerant flow and, consequently, higher power generated at the turbine generator and higher ORC efficiency. This was also observed under other solar radiation and other nanofluids with different concentrations.

6.1. Model Validation

To validate the numerical model presented here in equations (1) through (23), research work published in the literature on the subject in question, and it was found that very limited experimental data was published on the desalination by flashing technique using only water as base fluid; however, to our best knowledge, none was available using nanofluids. Therefore, it was decided to use the data published in reference Nannaronea et al [7] for validation purposes.

Figure 14 has been constructed to show a comparison between the results predicted by this model for the flashed flow and the data reported in reference [7]. As can be observed from this figure, the amount of the produced distillate decreases progressively along the stages and consequently as the flash temperature and pressure decrease profiles. This is due to the increase in the heat of vaporization at lower saturation temperatures, and therefore, a smaller amount of vapor is extracted from brine.

This figure depicts the flashed flow reduction ratio across the flashing chambers from the first to the last chamber. The data reported by reference [7] on the reduction ratio of the flashed flow was compared to the predicted results chamber by chamber.

The comparison clearly shows that the model compared well with the data; within the acceptable discrepancies of predicted and published experimental data, with relative errors of less than 4%, which is a very good agreement and demonstrates great confidence in the model.

The numerical predictions showed good agreement with the experimental measurements, with R^2 values greater than 0.95 and maximum relative deviations below 10%. The RMSE and MAE remained within the experimental uncertainty range. Because our system involves a magnetic field + nanoparticles, discrepancies of 5–10% can be quite reasonable because experimental results are affected by:

Nanoparticle agglomeration, uncertainty in nanoparticle concentration, magnetic field nonuniformity, viscosity changes, temperature-dependent properties, thermocouple accuracy, flow-rate measurement, heat losses, uncertainty in thermal conductivity correlations.

In addition, we believe that underprediction of the data is attributed to the energy loss to the surroundings in the form of Irreversible energy during the flashing process taking place in each chamber and was not fully considered by the mass and energy balances built in the present model, as can be seen in equation (16).

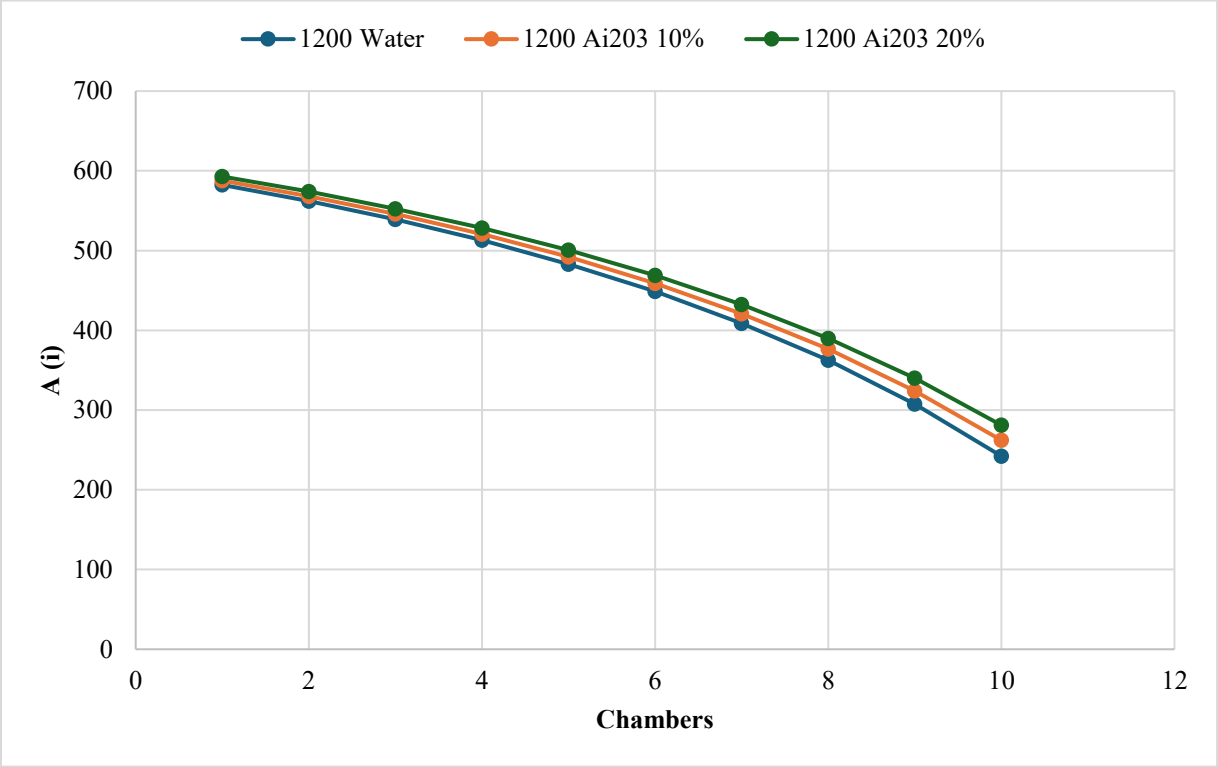

Fig. 12 Availability at different flashing chambers

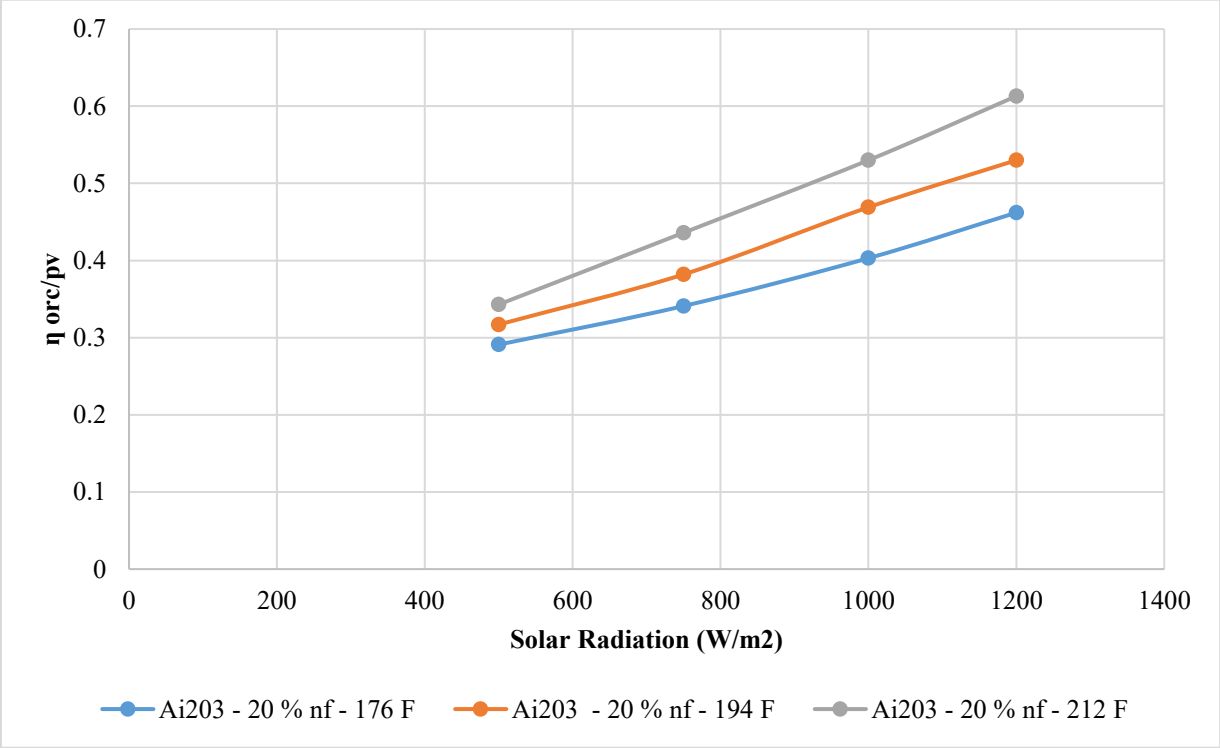

Fig 13 Hybrid System Efficiency

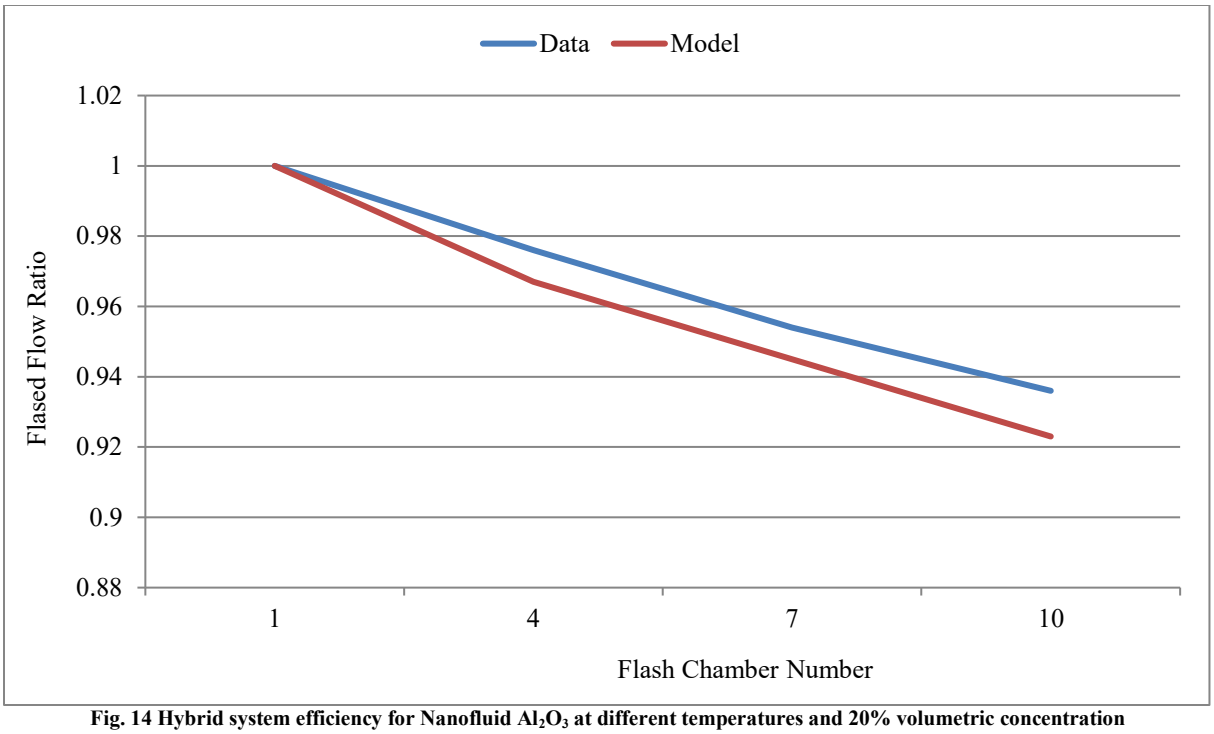

Fig. 14 Hybrid system efficiency for Nanofluid Al_2O_3 at different temperatures and 20% volumetric concentration

8. Challenges and Limitations

- High initial capital cost
- System complexity and integration challenges
- Intermittency of solar energy
- Maintenance of desalination units
- Optimization of energy distribution between subsystems

9. Future Research Directions

- AI-based optimization of energy flow and system control
- Integration with thermal energy storage systems
- Advanced materials for PVT collectors
- Hybrid desalination (thermal + membrane)
- Improved ORC working fluids for low-temperature heat

10. Conclusion

The integration of solar PVT systems with solar desalination and Organic Rankine Cycle offers a promising solution to the combined challenges of energy and water scarcity. By utilizing solar energy efficiently through cascading energy use, the system achieves higher overall performance compared to standalone technologies. Although challenges remain, ongoing technological advancements are expected to enhance feasibility and promote large-scale adoption.

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