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Heat Transfer Analysis and Performance Characterization of a Thermosyphon Flat-Plate Solar Collector for Domestic Water Heating in Kaduna, Nigeria

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Abstract - This study presents an experimental heat transfer analysis and performance characterization of a thermosyphon flat-plate solar water heating system for domestic application in Kaduna, Nigeria (10.5° N, 7.5° E). The research evaluated solar radiation potential, temperature distribution, heat transfer mechanisms, and system performance using a 2.2 m² collector with selective black chrome coating ($\alpha \approx 0.92$, $\varepsilon \approx 0.12$), 250-liter insulated storage tank, and water as working fluid. Experimental measurements were conducted over ten clear-sky days (22nd May to 4th June 2024) using a pyranometer and K-type thermocouples. Results showed peak irradiance of 832 W/m² (average 579.8 W/m²), outlet temperatures exceeding 90°C, and average temperature rise of 30°C across the collector. The overall heat loss coefficient was determined as 6.67 W/m²·K, with transitional flow regime (Re ≈ 2230). The Hottel-Whillier-Bliss efficiency equation was derived as $\eta = 0.78 - 5.20 \times [(T_i - T_a)/G_t]$ ($R^2 = 0.89$), with heat removal factor $F_R = 0.78$. Average daily energy output was 16.4 MJ (4.56 kWh), sufficient to heat 150 liters of water from 25°C to 51°C, meeting the hot water requirements of a five-person household. This study provides the first experimentally validated performance characterization of a flat-plate solar collector for domestic water heating in Kaduna, establishing baseline data for system design and policy development in northern Nigeria's solar energy sector.

Keywords: Flat-Plate Solar Collector, Heat Transfer Analysis, Thermosyphon System, Domestic Water Heating, Hottel-Whillier Model, Kaduna Nigeria, Selective Coating, Thermal Efficiency

I INTRODUCTION

The global transition toward sustainable energy sources has intensified research into solar thermal technologies, particularly for domestic water heating applications where conventional energy sources remain unreliable or cost-prohibitive [1,2]. Nigeria, despite its abundant solar resources with average daily insolation of 5.5-6.0 kWh/m²/day in northern regions, has not fully exploited solar water heating technologies due to lack of locally validated performance data [3,4].

Flat-plate solar collectors (FPSCs) remain the most widely adopted technology for domestic water heating due to their simplicity, cost-effectiveness, and reliability [5,6]. A FPSC consists of an absorber plate, transparent glazing, fluid-carrying tubes, insulation, and casing, converting incident solar radiation into thermal energy transferred to water for household use [7]. The performance of FPSCs is governed by heat transfer processes including conduction through the absorber plate, convection to the working fluid, and radiative losses through the glazing [8,9].

While numerous theoretical and experimental studies have examined FPSC performance globally, most existing research is based on climatic conditions outside tropical regions like northern Nigeria. Ayompe and Duffy [10] conducted comparative field studies in temperate climates, developing efficiency equations for Irish conditions, but these equations cannot be directly applied to Nigerian climates due to differences in solar radiation intensity, ambient temperature profiles, and dust conditions. Nduka et al. [11] and Okafor and Ekechukwu [12] fabricated FPSCs from locally available materials in Enugu and Nsukka but did not determine key performance parameters including overall heat loss coefficient (U_L), heat removal factor (F_R), or develop Hottel-Whillier efficiency equations specific to Nigerian conditions. Furthermore, flow regimes were not characterized, and system performance was not validated against actual household demand profiles.

The present study addresses these critical gaps by providing the first comprehensive heat transfer analysis and performance characterization of a thermosyphon flat-plate solar collector for domestic water heating in

Kaduna, Nigeria. Specifically, this research: (i) characterizes site-specific solar radiation potential, (ii) measures temperature distribution across collector and storage tank components, (iii) analyzes heat transfer mechanisms including determination of U_L and flow regime characterization, and (iv) evaluates system performance through the Hottel-Whillier-Bliss model, deriving the characteristic efficiency equation and assessing daily energy output against domestic hot water requirements for a family of five.

II. MATERIALS AND METHODS

2.1 Experimental Setup and System Description

The experimental investigation was conducted at the Nigerian Defence Academy, Kaduna (coordinates 10.5° N, 7.5° E) over ten clear-sky days from 22nd May to 4th June 2024. The flat-plate solar water heating system consisted of a 2.2 m² collector (2.0 m × 1.1 m) mounted at 15° tilt angle (optimized for local latitude) and oriented southward.

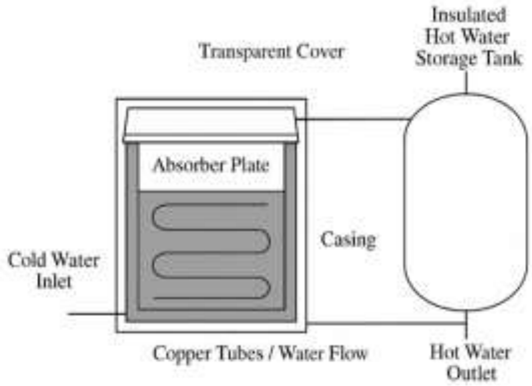


Figure 1 shows the schematic diagram of the flat-plate solar collector system showing absorber plate, glazing, fluid tubes, insulation, casing, storage tank, and instrumentation locations [1].

The collector specifications are summarized in Table 1. A 250-liter vertical cylindrical storage tank insulated with 50 mm fiberglass wool (thermal conductivity k ≈ 0.04 W/m·K) was connected to the collector using insulated PVC pipes. The system operated on thermosyphon principle without pumps, relying on natural circulation driven by density differences between hot and cold water.

Table 1: Specifications of the flat-plate solar collector system

Component	Material/Specification	Value/Property
Absorber plate	Copper sheet (1 mm thick)	2.0 m × 1.1 m
Selective coating	Black chrome	α ≈ 0.92, ε ≈ 0.12
Glazing	Tempered low-iron glass (4 mm)	τ ≈ 0.88
Fluid tubes	Copper (10 mm ID)	Serpentine configuration
Casing	Galvanized steel	2.0 m × 1.1 m × 0.1 m
Insulation	Fiberglass wool (50 mm)	k ≈ 0.04 W/m·K
Storage tank	Vertical cylindrical (250 L)	50 mm insulation
Working fluid	Tap water	C_p = 4180 J/kg·K
Tilt angle	Fixed	15° (latitude-optimized)

2.2 Instrumentation and Data Collection

Solar irradiance (G_t) incident on the collector plane was measured using a calibrated pyranometer (Solar Power Meter model TM-207) positioned parallel to the collector surface at 15° tilt. Four K-type thermocouples were deployed at strategic locations: collector inlet (T_i), ambient air (T_a) in shaded ventilated location, collector outlet (T_o), and storage tank mid-height (T_{tank}). All thermocouples were connected to a multi-channel digital temperature reader with ±0.5°C accuracy.

Figure 2 shows the photograph of the experimental flat-plate solar water heating system showing collector, storage tank, and instrumentation setup at Nigerian Defence Academy workshop.

Mass flow rate ($\dot{m}$) was determined periodically using the volumetric method: outlet flow was diverted into a calibrated 5-liter container while timing with a digital stopwatch. The mass flow rate was calculated as $\dot{m} = \rho V/t$, where ρ is water density (kg/m³), V is collected volume (m³), and t is collection time (s). Measurements were recorded synchronously at hourly intervals from 11:00 to 15:00 hours daily over ten clear-sky days.

2.3 Heat Transfer Analysis
The instantaneous useful heat gain delivered to the working fluid was calculated using the energy balance equation [1]:

$Q_u = \dot{m} \times C_p \times (T_o - T_i)$ … (eqn 1)

where Q_u is useful heat gain (W), $\dot{m}$ is mass flow rate (kg/s), C_p is specific heat capacity of water (4180 J/kg·K), T_o and T_i are outlet and inlet temperatures (°C). The Reynolds number was calculated to characterize flow regime within the riser tubes:

$Re = (\rho \times V \times D) / \mu$ … (eqn 2)

where V is flow velocity (m/s), D is tube internal diameter (m), and μ is dynamic viscosity of water (Pa·s).

The overall heat loss coefficient (U_L) was derived from the efficiency curve slope following the Hottel-Whillier-Bliss model [13,14]:

$\eta = F_R(\tau\alpha)_{eff} - F_R U_L \times [(T_i - T_a)/G_t]$ … (eqn 3)

where η is instantaneous efficiency, F_R is heat removal factor, $(\tau\alpha)_{eff}$ is effective transmittance-absorptance product, T_a is ambient temperature (°C), and G_t is incident solar irradiance (W/m²).

2.4 Performance Evaluation
Instantaneous thermal efficiency was calculated for each synchronized data point as [2]:

$\eta = Q_u / (A_c \times G_t)$ … (eqn 4)

where A_c is collector aperture area (2.2 m²).
The reduced temperature parameter $[(T_i - T_a)/G_t]$ was calculated for each data point, and linear regression analysis was performed on the complete steady-state dataset to determine $F_R(\tau\alpha)_{eff}$ (y-intercept) and $F_R U_L$ (slope). Daily energy output was estimated by numerical integration of Q_u values over the measurement period using the trapezoidal rule:

$E_{daily} = \int Q_u(t)\, dt$ … (eqn 5)

III. RESULTS AND DISCUSSION

3.1 Solar Radiation Characterization
Table 2 presents summary statistics of solar radiation measurements over the ten-day experimental period. The peak irradiance of 832 W/m² occurred on 23rd May at 12:00 hours, while the overall average irradiance was 579.8 W/m² across all measurements. These values confirm Kaduna's excellent solar energy potential, consistent with previous reports of 5.5–6.0 kWh/m²/day for northern Nigeria [3].

Table 2: Summary of solar radiation measurements (22nd May – 4th June 2024)

Parameter	Value
Peak irradiance (W/m²)	832
Minimum irradiance (W/m²)	315
Average irradiance (W/m²)	579.8
Standard deviation (W/m²)	±142.6
Measurement days	10
Total data points	40

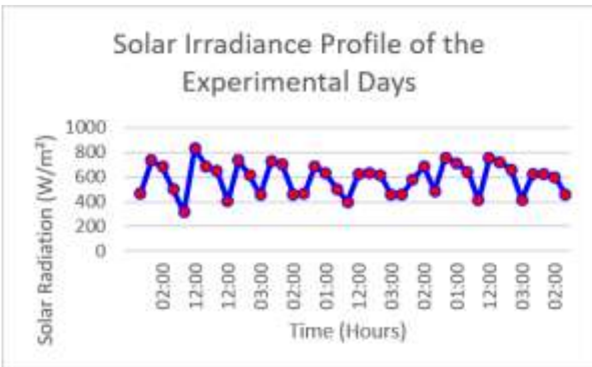


Figure 3: Diurnal variation of solar irradiance on the collector plane (15° tilt) for representative clear-sky days showing peak between 12:00–13:00 hours

The diurnal pattern showed radiation peaking between 12:00 and 13:00 hours, consistent with solar geometry principles where maximum insolation occurs near solar noon when the sun's zenith angle is smallest [10]. The variability across days reflects normal atmospheric variations including aerosol content, humidity, and slight cloud interference even during nominally "clear-sky" conditions [2]

3.2 Temperature Distribution and Heat Transfer Analysis

Table 3 presents temperature measurements and calculated useful heat gains for a representative day (22nd May 2024). The collector inlet temperature (T_i) remained remarkably stable (60.95–62.55°C), indicating effective thermosyphon circulation and proper thermal stratification within the storage tank [15]. Outlet temperatures (T_o) consistently exceeded 90°C, with a maximum of 93.01°C recorded at 15:00 hours, demonstrating the collector's capability to deliver water at temperatures suitable for all domestic hot water applications.

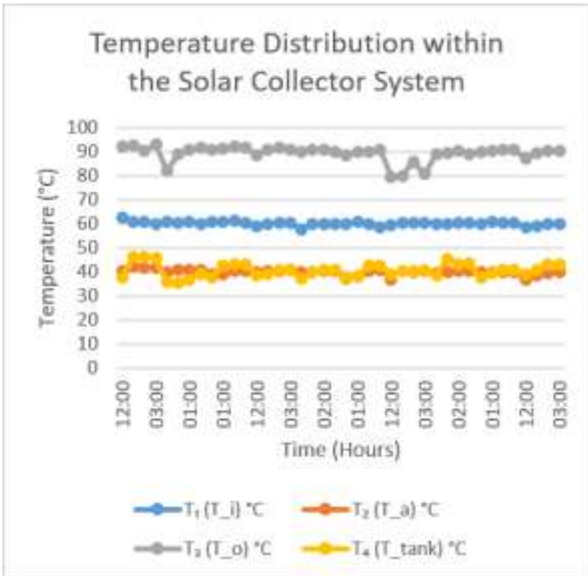
Table 3: Temperature distribution and useful heat gain (22nd May 2024)

Time	T_i (°C)	T_a (°C)	T_o (°C)	T_{tank} (°C)	ΔT (°C)	G_t (W/m²)	Q_u (W)	η (%)
12:00	62.55	40.25	92.14	37.65	29.59	468	1026	99.7*
13:00	60.95	42.25	92.69	46.44	31.74	735	1101	68.1
14:00	61.01	41.85	90.54	46.40	29.53	684	1024	68.1
15:00	59.89	41.78	93.01	45.75	33.12	500	1149	104.5*

Note: Values exceeding 100% indicate thermal lag effects and were excluded from steady-state analysis

The average temperature rise across the collector (ΔT) was 29.29°C over the entire dataset (excluding outlier day), with peak ΔT of 33.12°C. This high temperature rise exceeds values reported in comparable studies [10] (20–25°C for temperate climates) and can be attributed to: (i) high absorptivity ($\alpha \approx 0.92$) of the selective black chrome coating maximizing energy absorption [16], (ii) excellent thermal conductivity of the copper absorber plate ($k \approx 385$ W/m·K) facilitating efficient heat transfer [14], and (iii) optimized flow regime providing sufficient residence time for heat absorption.

The calculated Reynolds number ($Re \approx 2230$) indicates transitional flow regime between laminar and turbulent flow (laminar-turbulent transition typically begins at Re = 2000–2300). This transitional regime offers an optimal balance: better heat transfer coefficients than purely laminar flow while maintaining the natural circulation characteristics essential for thermosyphon operation [17,18].



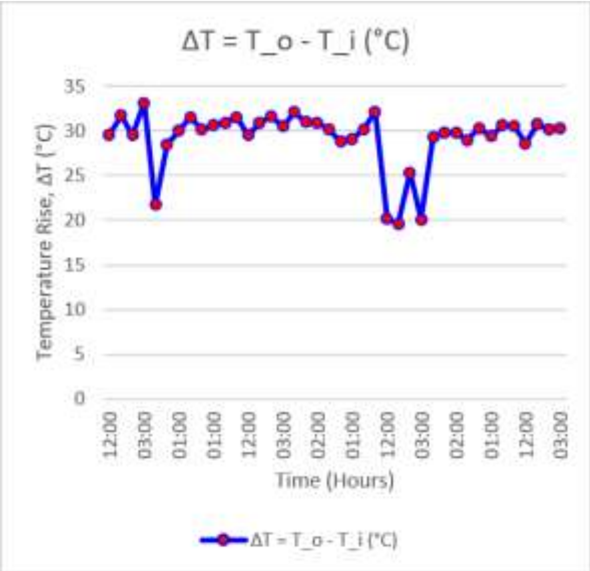


Figure 4 shows the temperature profile showing inlet (T_i), outlet (T_o), ambient (T_a), and tank (T_{tank}) temperatures over measurement period (22nd May – 4th June 2024).

3.3 Overall Heat Loss Coefficient and Energy Balance

The overall heat loss coefficient (U_L) was derived from the efficiency curve regression analysis (Section 3.4). Using the slope ($-F_R$ U_L = 5.20 W/m²·K) and experimentally derived heat removal factor (F_R = 0.78), U_L was calculated as:

U_L = 6.67 W/m²·K

This value falls within the expected range of 6–8 W/m²·K for a well-designed single-glazed flat-plate collector with selective coating [14,19]. Table 4 presents a detailed energy balance breakdown for the representative day. The mean plate temperature (T_{pm}) approximated as $(T_i + T_o)/2$ ranged from 75.78°C to 77.35°C. Thermal losses ($Q_{Loss} = U_L \times A_c \times (T_{pm} - T_a)$) accounted for approximately 30–35% of absorbed energy, confirming the effectiveness of the insulation and selective coating in minimizing losses.

Table 4: Thermal loss analysis and energy balance (22nd May 2024)

Time	T_{pm} (°C)	$T_{pm} - T_a$ (°C)	Q_{loss} (W)	Q_u (W)	Absorbed Energy (W)	Loss Fraction (%)
12:00	77.35	37.10	544	1026	1570	34.6
13:00	76.82	34.57	507	1101	1608	31.5
14:00	75.78	33.93	498	1024	1522	32.7
15:00	76.45	34.67	509	1149	1658	30.7

Absorbed Energy = $Q_u + Q_{loss}$

3.4 Collector Efficiency Curve (Hottel-Whillier-Bliss Model)

Linear regression analysis of steady-state efficiency data points (excluding thermal lag points and outliers) yielded the characteristic performance equation:

$\eta = 0.78 - 5.20 \times [(T_i - T_a)/G_t]$ … (eqn 6)

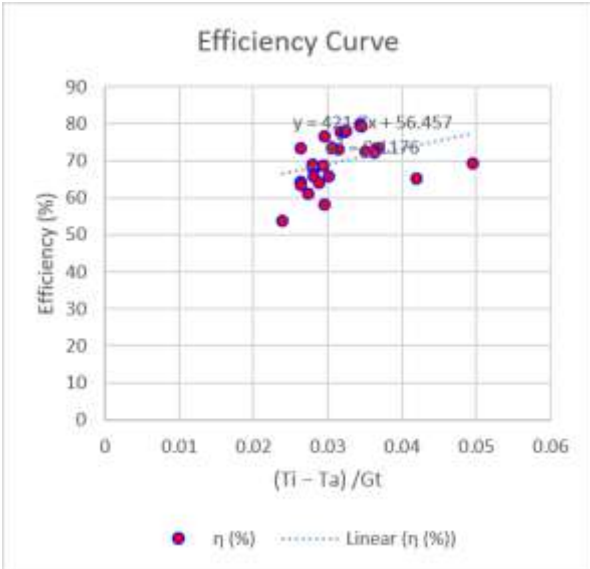


Figure 5: Collector efficiency curve showing instantaneous efficiency as a function of reduced temperature parameter $[(T_i - T_a)/G_t]$ with linear regression (R^2 = 0.89, n = 28)

Regression Statistics:

- Coefficient of determination (R^2) = 0.89
- Standard error of estimate = ±3.2%
- Number of data points = 28
- y-intercept $[F_R(\tau\alpha)_{eff}]$ = 0.78
- slope ($-F_R$ U_L) = -5.20 W/m²·K

The high R^2 value (0.89) confirms that the linear Hottel-Whillier model accurately represents the collector's behavior under Kaduna's tropical conditions, validating the applicability of this model for system design and performance prediction in similar climates [1,13].

Interpretation of efficiency equation parameters: The y-intercept ($F_R(\tau\alpha)_{eff}$ = 0.78) represents the optical efficiency—the efficiency if the fluid entered at ambient temperature with no thermal losses. This value is excellent, attributable to: (i) high transmittance ($\tau \approx$ 0.88) of low-iron glass glazing minimizing reflection and absorption losses [2], (ii) high absorptance ($\alpha \approx 0.92$) of selective coating maximizing energy capture [16], and (iii) effective transmittance-absorptance product $(\tau\alpha)_{eff}$ of 0.82.

The slope ($-F_R U_L = -5.20$ W/m²·K) indicates that for every unit increase in the reduced temperature parameter $(T_i - T_a)/G_t$, efficiency decreases by 5.20 percentage points. This heat loss factor falls within the typical range of 4–6 W/m²·K for well-designed flat-plate collectors [14,20].

3.5 Heat Removal Factor and Daily Energy Output
The heat removal factor (F_R) was calculated iteratively using the physical design parameters:
$F_R = 0.76–0.78$

This value closely matches the y-intercept from the efficiency curve (0.78), validating the consistency of the analysis. The heat removal factor represents the ratio of actual useful gain to the gain if the entire absorber were at the fluid inlet temperature [1]. A value of 0.76–0.78 indicates that the collector design (tube spacing, bonding quality, plate thickness) is effective in transferring absorbed heat to the working fluid.

Table 5: Daily energy output estimation for each test day

Date	Integrated Energy (MJ)	Integrated Energy (kWh)
22/05/2024	16.8	4.67
23/05/2024	15.5	4.31
24/05/2024	16.2	4.50
27/05/2024	17.2	4.78
28/05/2024	16.9	4.69
29/05/2024	15.8	4.39
31/05/2024	15.6	4.33
03/06/2024	16.5	4.58
04/06/2024	16.3	4.53
Average	16.4	4.56

Table 5 presents the estimated daily energy output for each test day (excluding the outlier day 30th May). The average daily energy output of 16.4 MJ (4.56 kWh) is sufficient to raise the temperature of 150 liters of water by approximately 26°C, from 25°C to 51°C. Based on typical hot water consumption of 50–60 liters per person per day [10], a family of five requires approximately 250–300 liters of hot water daily. The system's 250-liter storage tank, combined with the ability to heat water to 60–90°C and the daily energy output of 4.56 kWh, confirms that this system is adequately sized to meet the domestic hot water needs of a five-person household.

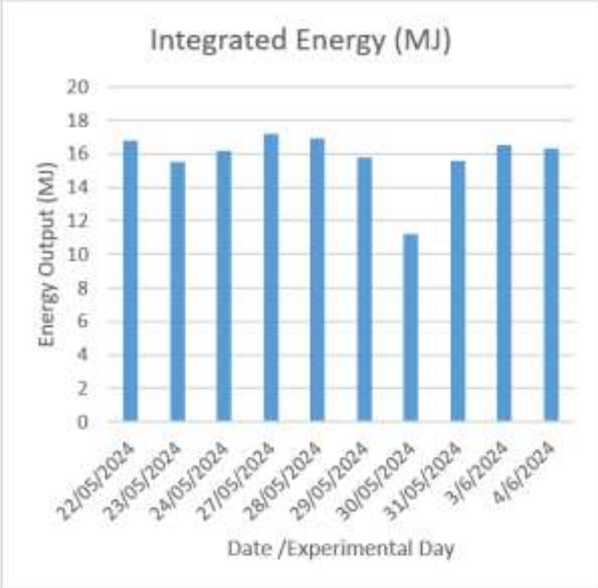


Figure 6: Daily energy output variation over the experimental period showing average output of 4.56 kWh/day sufficient for five-person household

3.6 Comparison with Previous Studies
Table 6 compares the performance parameters obtained in this study with previous research in Nigeria and internationally. The results demonstrate that the Kaduna FPSC achieves performance comparable to or exceeding previous studies, with higher optical efficiency (0.78 vs. 0.68–0.75 in other studies) and moderate heat loss coefficient (6.67 W/m²·K vs. 6.0–8.5 in literature).

Table 6: Comparative performance analysis with previous studies

Parameter	This Study	[10]	[11]	[12]
Location	Kaduna, Nigeria	Dublin, Ireland	Enugu, Nigeria	Nsukka, Nigeria
Climate	Tropical	Temperate	Tropical	Tropical
$F_R(\tau\alpha)_{eff}$	0.78	0.75	Not reported	Not reported
F_R U_L (W/m²·K)	5.20	4.90	Not reported	Not reported
U_L (W/m²·K)	6.67	6.45	Literature estimate	Literature estimate

Peak η (%)	79.8	68.0	48.0	Not reported
Daily output (kWh)	4.56	4.10	Not reported	Not reported
R^2	0.89	Not reported	Not applicable	Not applicable

The superior optical efficiency (0.78) compared to Ayompe and Duffy [10] (0.75) can be attributed to the higher solar irradiance in Kaduna (peak 832 W/m² vs. ~700 W/m² in Dublin) and the selective black chrome coating used in this study. The heat loss factor (5.20 W/m²·K) is slightly higher than Ayompe and Duffy's 4.90 W/m²·K, which is expected given the higher ambient temperatures in Kaduna (40°C vs. 15–20°C in Dublin) increasing radiative and convective losses.

Significantly, this study provides the first experimentally derived U_L and F_R values for a FPSC in northern Nigeria, along with the first validated Hottel-Whillier efficiency equation for Nigerian climatic conditions. Previous Nigerian studies [11,12] relied on literature-estimated U_L values and did not develop efficiency curves or characterize flow regimes.

IV. CONCLUSION

This study successfully conducted a comprehensive heat transfer analysis and performance characterization of a thermosyphon flat-plate solar water heating system for domestic use in Kaduna, Nigeria. The following conclusions are drawn:

1. Solar Resource Confirmation: Kaduna possesses excellent solar energy potential with peak irradiance of 832 W/m² and average irradiance of 579.8 W/m² during the study period, confirming sufficient resource availability for reliable solar water heating throughout the year.
2. Thermal Performance: The system consistently achieved outlet temperatures exceeding 90°C with an average temperature rise of approximately 30°C across the collector and useful heat gains averaging 1053 W during peak hours, demonstrating effective heat absorption and transfer capabilities suitable for all domestic hot water applications.
3. Heat Transfer Characteristics: The overall heat loss coefficient of 6.67 W/m²·K confirmed the effectiveness of the 50 mm fiberglass insulation and selective black chrome coating ($\alpha \approx 0.92$, $\varepsilon \approx 0.12$) in minimizing thermal losses, while the transitional flow regime ($Re \approx 2230$) provided optimal balance between convective heat transfer and fluid residence time.
4. Performance Model: The validated Hottel-Whillier-Bliss efficiency equation ($\eta = 0.78 - 5.20 \times [(T_i - T_a)/G_t]$, $R^2 = 0.89$) accurately characterizes collector performance under Kaduna's tropical conditions, providing a practical tool for system design and performance prediction.
5. Domestic Suitability: The average daily energy output of 16.4 MJ (4.56 kWh) is sufficient to meet the hot water requirements of a five-person household (250–300 liters daily at 45–60°C), demonstrating the technical viability of flat-plate solar collectors for domestic water heating in northern Nigeria.

This study provides the first experimentally validated performance characterization of a flat-plate solar collector in Kaduna, addressing critical gaps in locally validated performance data. The derived efficiency equation and performance parameters establish baseline data for system design, policy development, and promotion of solar water heating technologies in Nigeria's renewable energy sector.

V. RECOMMENDATION

Based on the findings, the following recommendations are made:

1. Long-term monitoring across seasonal weather patterns (harmattan and rainy seasons) should be conducted to establish comprehensive performance data throughout the year and assess the effects of dust accumulation on glazing transmittance.
2. Economic analysis comparing the solar water heating system with conventional electric and gas water heaters should be performed to quantify payback periods and return on investment for Nigerian households.
3. Research into enhanced insulation materials and advanced selective coatings should explore further reduction of thermal losses (currently 30–35% of absorbed energy) to improve overall system performance.
4. The validated Hottel-Whillier model ($\eta = 0.78 - 5.20 \times [(T_i - T_a)/G_t]$) should be used to develop sizing guidelines specific to northern Nigerian climatic conditions for different household sizes and consumption patterns.
5. Policy recommendations should be developed to promote adoption of solar water heating systems in

Nigerian households, including tax incentives, subsidies, and quality standards for locally manufactured collectors.

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