Experimental study of heat retention performance of thermal-diode Integrated Collector Storage Solar Water Heater (ICSSWH) configurations

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Abstract

Integrated Collector Storage Solar Water Heaters (ICSSWHs) can support growing hot water demands of off-grid populations and reduce harm to human health and the environment. Despite their simple design and fewer associated components, stored thermal energy dissipates easily in foul weather. While thermal-diodes are beneficial heat retention enhancement features in ICSSWHs, other simple additional strategies can enhance heat retention without significantly complicating the fabrication process. This article examines techniques of differing levels of complexity for the improvement of heat retention of a basic thermal-diode ICSSWH. A basic thermal diode ICSSWH is adapted into a scalable Asymmetric Formed Reflector with Integrated Collector and Storage (AFRICaS) system and tested for heat retention performance along with other thermal insulation measures. The AFRICaS system improves heat retention efficiency and reduces heat loss coefficient to at least 35% and 1.46 W/K respectively. These results contrast with a heat retention efficiency and heat loss coefficient of 20% and 2.29 W/K respectively for a basic thermal diode ICSSWH. The AFRICaS prototype is potential launchpad for sustainable solar energy cogeneration.

Introduction

Off-grid populations in developing countries live under a double-edged energy dilemma. They are off the electricity grid and they depend on traditional energy fuels (fuelwood, charcoal, paraffin, straw, animal waste, crop residues etc.) for their energy needs. Their electrical energy consumption is low whilst their thermal energy consumption is significant but depends on inefficient combustion of low quality fuels. A typical 5-person off-grid household may have electricity consumption as low as 6.3 kWh per month whilst thermal energy consumption via fuelwood sources could reach 5.5 GJ per month [1]. Ouedraogo [2] has empirically shown that lack of sufficient energy impairs human development and stifles macro and micro-economic development of societies. Additionally, heavy reliance on traditional energy fuels promotes environmental harm and indoor air pollution resulting in an estimated 1.6 million premature deaths [3] and 4.3 million health ailments [4] every year. One approach to mitigating this scenario is to harness renewable energy resources for locations where they exist in abundance. According to Qurashi et al [5], the greatest amount of solar energy resources are located between latitudes 15° to 35° north and south of the equator which is also the region dominated

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by the world's energy poor. Solar energy offers the promise of realising affordable systems that employ functional attributes of currently available technologies to bring modern energy to the deprived.

Innovative Integrated Collector Storage Solar Water Heater (ICSSWH) designs with a thermal diode have been extensively researched over the years at the Centre for Sustainable Technologies, Ulster University for over a decade [6–11]. A thermal diode is a mechanical technique that enhances solar heat collection and minimises the loss of collected heat during the night and overcast periods. Just like an electrical semiconductor diode, it achieves this via its characteristic low resistance to heat flow in one direction and higher resistance in the reverse direction [7]. The originally patented vertically operating thermal diode ICSSWH concept [12] is in commercialisation stages [13] but recent variants have evolved into horizontally operating versions [9]. Commercialisation of both variants of the thermal diode ICSSWH is under the trade name 'SolaCatcher' [13]. In the current research, a horizontally operating version of a thermal diode ICSSWH is adapted to configure a scalable system that could potentially maximise locally available solar energy for domestic applications under a reduced system footprint. Fig. *1* is a cutaway illustration of the basic horizontally operating thermal diode ICSSWH apparatus with the absorber (outer vessel) coated with matt black paint with absorptivity ($\alpha \cong 0.90$), emissivity ($\varepsilon \cong 0.95$) and reflectivity ($\rho \cong 0.1$).

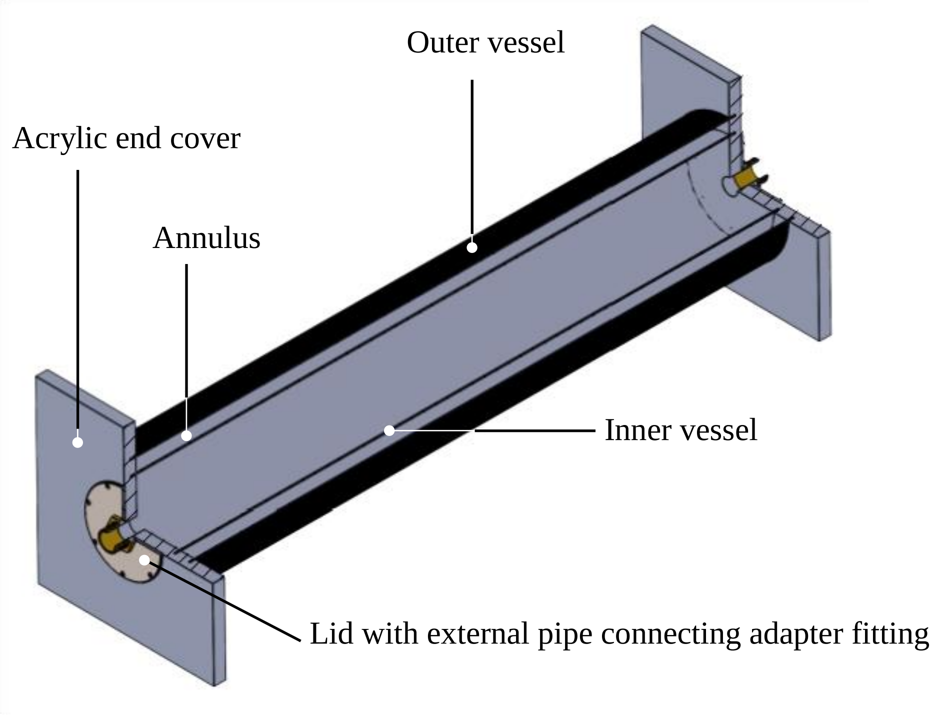


Fig. 1. The basic horizontally operating thermal diode ICSSWH apparatus [11]

The main functional character of the thermal diode ICSSWH resides in the thermally driven transformations undergone by the small volume of phase change liquid present in the partially evacuated annulus. De Beijer [14] who also formulated a closely related solar hot water heater provides a concise description of the working principle of this kind of thermal diode. The basic thermal diode ICSSWH has a full length of 1021 mm including its cylindrical concentric vessels with end caps. The effective absorbing surface length of the basic thermal diode ICSSWH is 981 mm and the diameters of the outer vessel and inner vessel are 200 mm and

150 mm respectively. The outer absorbing cylinder is fabricated from 2 mm thick aluminium and the inner vessel is fabricated from 1.2 mm thick stainless steel, creating an evacuated annular space of approximately 22 mm between the two concentric vessels. A stainless steel plate is integrated into the end cap to support the inlet and outlet connections. The volumetric capacity of the thermal diode ICSSWH is approximately 17 litres. Material, performance and cost considerations dictating the realisation of affordable and lightweight horizontally operating thermal diode ICSSWHs are published elsewhere [11].

Since the phase change liquid settles at the bottom of the annular space, the solar energy collection efficiency of the basic thermal diode ICSSWH is likely to be enhanced if the solar radiation is uniformly distributed around the bottom section of absorber vessel. Only, a simple non-imaging reflector with a wide acceptance angle could achieve this albeit with a geometric concentration ratio of unity. Such a non-imaging reflector is an involute, has a significant field of view for all incoming direct and diffuse solar radiation and is well suited for low temperature solar thermal applications in equatorial locations. This paper introduces a novel prototype of Asymmetric Formed Reflector with Integrated Collector and Storage (AFRICaS) and presents insights gained from experimental testing of various heat loss management approaches in horizontally operating thermal diode ICSSWH concepts.

AFRICaS concept and geometrical features

The central component of the AFRICaS system concept is the basic thermal diode ICSSWH as shown in Fig. 1. The geometrical dimensions of the basic thermal diode ICSSWH determine the overall geometry of the AFRICaS unit to a full system length of 1108 mm. Fig. *2* is a side section view of the system and its associated functional features. Not only does the AFRICaS system have enhanced solar heat collection functionality, it also possesses heat loss management strategies all implemented to form an improved solar thermal device. In addition, the single glazed system enclosure provides a planer area measuring approximately 523 mm x 1108 mm (~ 0.58 m^2) atop the insulation for a standard photovoltaic module whilst housing electrical storage in the cavity underneath the reflector. The AFRICaS design enables light distribution and concentration onto three-quarters of the aluminium absorber surface of the basic thermal diode ICSSWH, dictating insulation of the one-quarter of the remaining absorber surface. Fig. *3* depicts a completed fabrication of the AFRICaS experimental prototype (hereinafter described as AFRICaS-ICSSWH A).

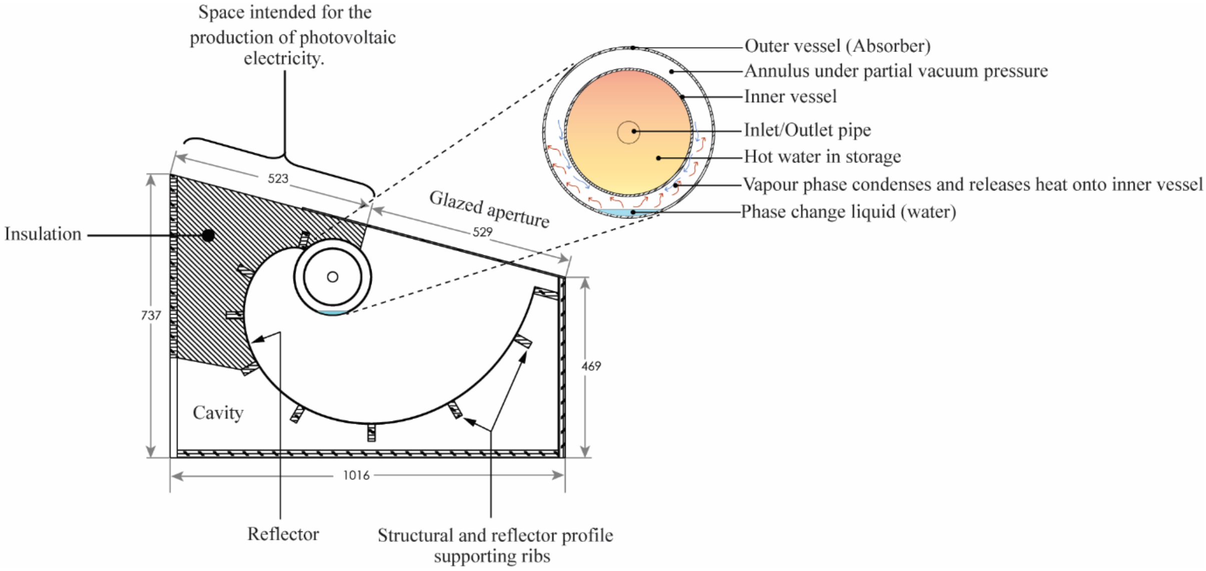


Fig. 2. Structural configuration and geometry of the AFRICaS system

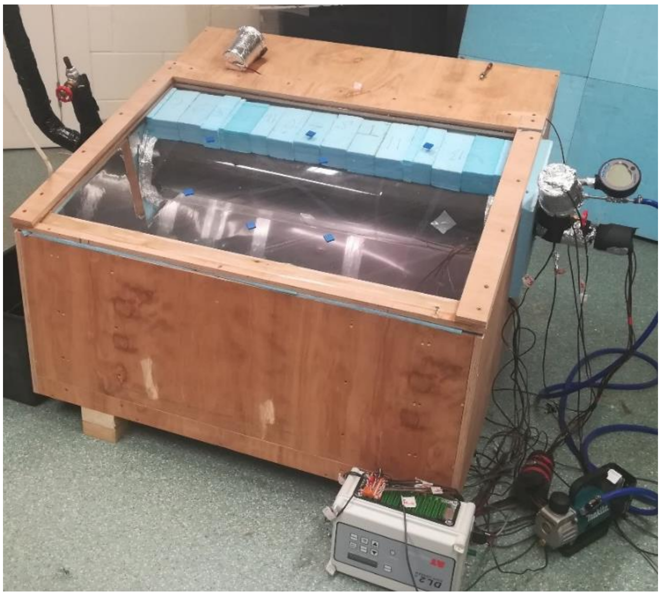
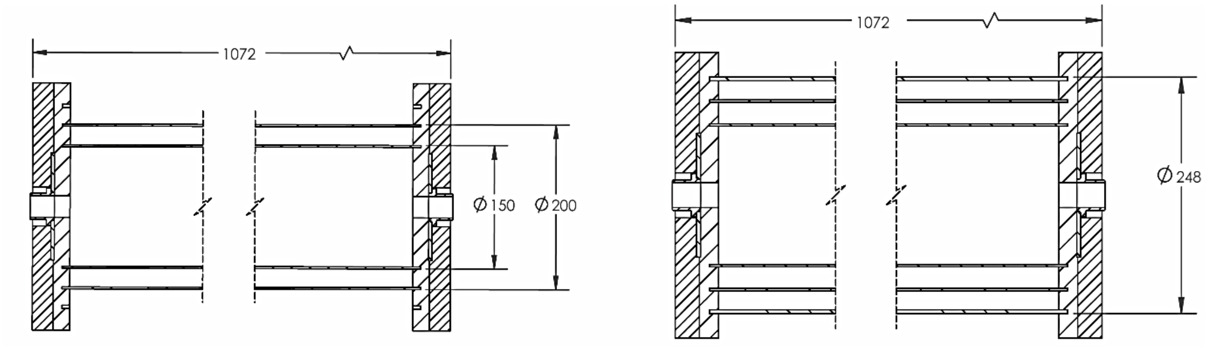


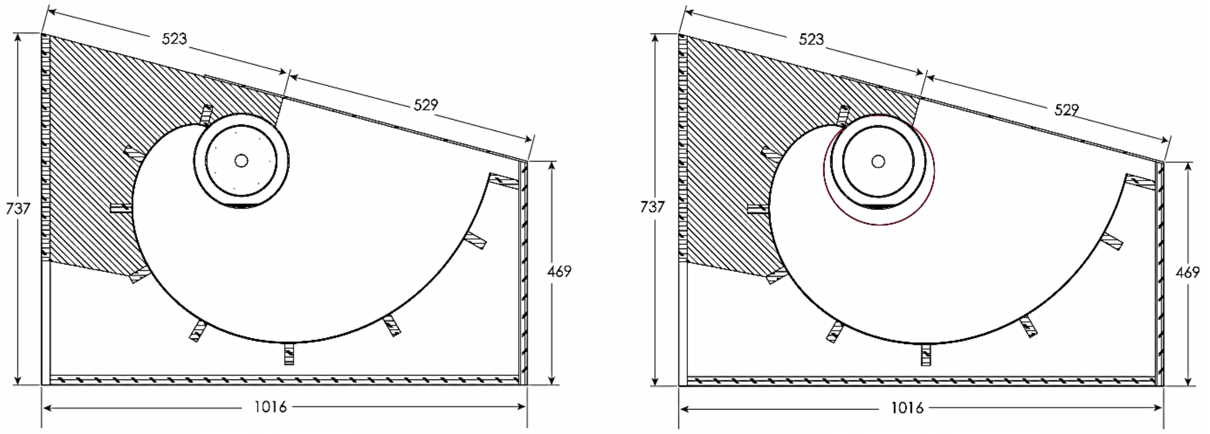
Fig. 3. An image of the completed AFRICaS ICSSWH system under experimental preparation

Description of the ICSSWH system variants

The introduction of the various heat loss management features on the basic thermal diode ICSSWH (shown in Fig. 1 and hereinafter described as TD-ICSSWH A) resulted in four additional system configurations i.e. two variants of the basic concept, TD-ICSSWH B and TD-ICSSWH C and two variants of the AFRICaS concept, AFRICaS-ICSSWH A and AFRICaS-ICSSWH B. While TD-ICSSWH A has no additional heat loss protection features, TD-ICSSWH B has insulation at both end covers and TD-ICSSWH C has end cover insulation and a concentric transparent cover around the outer vessel (absorber). Thus heat loss via the end plates and convective heat loss around the outer vessel are minimised. AFRICaS-ICSSWH A comprises an adaptation of TD-ICSSWH A in a thermal enclosure as shown in Fig. 2 while AFRICaS-ICSSWH B introduces a transparent enclosure fitted around the exposed three-quarter surface area of the absorber vessel. Fig. *4* depicts sectional views of the four ICSSWHs additional variants and the implemented thermal insulation measures. In total, the investigation covered five concepts including the basic TD-ICSSWH A.



(a) TD-ICSSWH B **(b)** TD-ICSSWH C



(c) AFRICaS-ICSSWH A **(d)** AFRICaS-ICSSWH B

Fig. 4. ICSSWH variants and associated heat loss management features: **(a) TD-ICSSWH B**, has insulation on both end covers of the basic thermal diode ICSSWH, **(b) TD-ICSSWH C**, has a transparent concentric cover added to TD-ICSSWH B, supressing convective heat loss around the outer vessel (absorber), **(c) AFRICaS-ICSSWH A**, is an adaptation of TD-ICSSWH B into the novel AFRICaS unit with inverted reflector and a single glazed thermal enclosure, **(d) AFRICaS-ICSSWH B**, is identical to AFRICaS-ICSSWH A but has a transparent cover around three-quarter of the absorber vessel.

Testing methodology and data reduction

The heat retention testing methodology comprises an energy loss test procedure as described by Zollner et al [15]. The test introduces hot water at a desired temperature into the ICSSWH collector. Then it allows the hot water filled system to cool for a desired monitored period under constant ambient air conditions without solar irradiation. Initially, the basic TD-ICSSWH A was filled with hot water, purged of air bubbles. Then it was utilised in five subsequent experimental configurations to allow detectable observations. An improvised system vent pipe allowed the complete removal of all air bubbles from within the tank and bringing the tank to full capacity. Every minute, a Delta-T DL2e data logger recorded temperature measurements retrieved via T-type Copper/Constantan thermocouples with five installed along the centreline of the storage vessel to measure hot water temperature and four installed in the conditioned indoor environment to measure ambient air temperature. To begin each experiment, a battery-powered vacuum pump (Makita DVP180Z) created a partial vacuum pressure of 24 mbar relative to the prevailing atmospheric pressure in Belfast within the annular thermal diode. Vacuum pressure measurement utilised a digital pressure gauge (Druck DPI104-1). An external hot water system i.e. a refrigerated/ heating circulator (Julabo FP 50) circulated hot water in each configured prototype until the five hot water measurements along the storage vessel reached a uniform value of 55±0.5°C. Each configured prototype cooled naturally in a conditioned ambient environment for a period of 14 hours after disconnecting heating and circulation. The experiments simulated the cooling behaviour of the devices with no draw off. A 14-hour retention period is typical for characteristic equatorial locations where such solar thermal collectors could have collection periods in excess of 10 hours during the day.

The analysis of average hot water and average ambient air temperature recordings derived average cooling profiles. Calculation of heat retention efficiency, η_{ret} utilised the data reduction equation stated as:

$$\eta_{\mathrm{ret}} = \left(T_f - T_a\right)/\left(T_i - T_a\right) \tag{1}$$

where T_i and T_f (in °C) are initial and final average hot water temperatures at the beginning and end of the testing period and T_a is the average ambient air temperature. Finally, the calculation of the overall heat loss coefficient, U_L (in W/K) of each configuration utilised the data reduction equation stated as:

$$U_L = \left[M_f c_p/\Delta t\right].\ln\left[\left(T_i - T_a\right)/\left(T_f - T_a\right)\right] \tag{2}$$

where M_f is the mass of water in the storage vessel (in kg), c_p the specific heat capacity of water (in $\mathrm{Jkg^{-1}K^{-1}}$) and Δt the heat retention testing period (in seconds). Zollner et al [15] discusses aspects concerning the repeatability of this methodology and considerations for extending indoor testing results to make outdoor performance predictions.

Results and discussion

The normalised hot water cooling profiles as well as the prevailing measured average ambient air temperature for a 14-hour monitoring period are shown in Fig. *5*. Clearly, the various modifications described in Fig. 4 show a positive influence on the cooling rates of the tested ICSSWH configurations. The family of thermal diode ICSSWH devices depict higher cooling rates than the two AFRICaS-ICSSWH device configurations. Fig. *6* shows that hot water temperature retained by the configured ICSSWH devices after a 14 hours were 27.1 °C, 30.1 °C, 31.7 °C, 32.6 °C and 33.4 °C for TD-ICSSWH A, TD- ICSSWH B, TD- ICSSWH C, AFRICaS- ICSSWH A and AFRICaS- ICSSWH B respectively. The initial water temperature differed slightly across the configured concepts and was 54.96±0.14 °C while the average ambient air temperature during the monitoring period of all configurations was 20.31±0.21 °C. At the end of the monitoring period, AFRICaS-ICSSWH A and AFRICaS-ICSSWH B configurations produced the highest temperature difference between the water in storage and ambient air reaching 12.4 °C and 13.3 °C respectively. In contrast, TD-ICSSWH A, TD-ICSSWH B and TD- ICSSWH C produce a low temperature difference between the water in storage and ambient air of 7.9 °C, 9.8 °C and 11.9 °C, respectively.

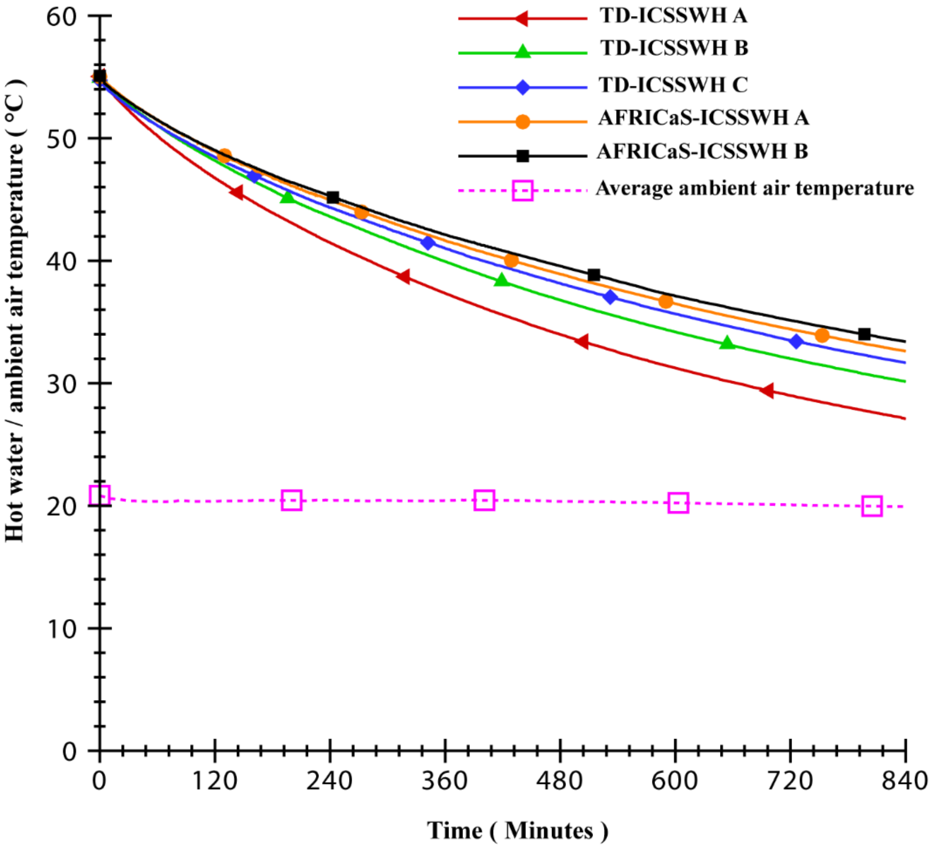


Fig. 5. Actual hot water temperature during the 14 h cooling period and average ambient air temperature

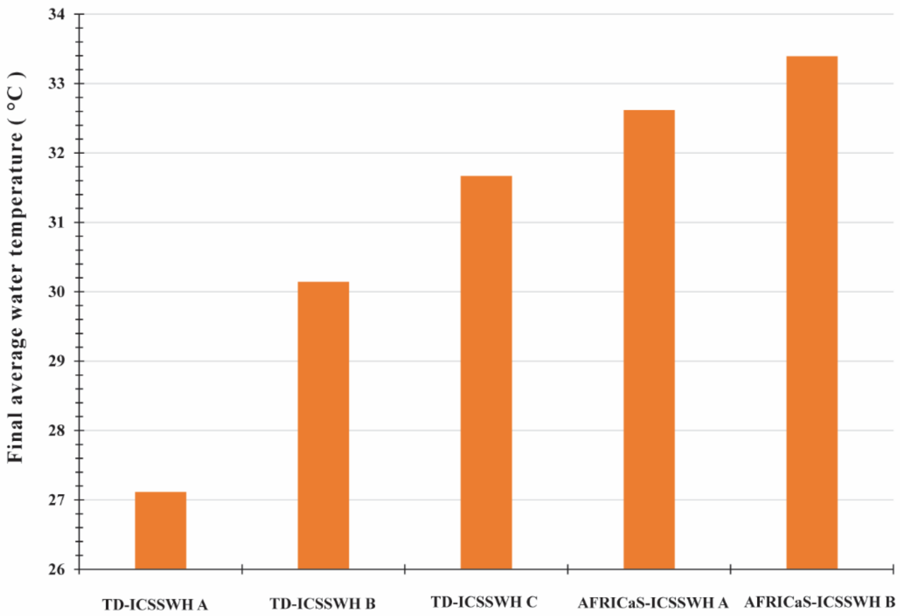


Fig. 6. Final water temperature after the 14 h system cooling period

Finally, the calculated heat retention efficiencies and the heat loss coefficients for all the tested device configurations are shown in Fig. *7* for the 14-hour monitoring period. AFRICaS-ICSSWH B attained the highest retention efficiency of 37.6% and the lowest heat loss coefficient of 1.36 W/K. The retention efficiency and the heat loss coefficient for the

AFRICaS-ICSSWH A configuration were correspondingly 2.4% lower and 6.4% greater than for the AFRICaS-ICS B configuration. The heat loss reduction measures implemented amongst the three basic TD-ICSSWH device configurations resulted into the greatest improvement in retention efficiencies and heat loss coefficients from 20% and 2.29 W/K respectively for TD-ICSSWH A to 33.5% and 1.53 W/K respectively for TD-ICSSWH C. The overall increase in retention efficiency between the TD-ICSSWH A and AFRICaS-ICSSWH configurations reached 15.2% and 17.6% for AFRICaS-ICSSWH A and AFRICaS-ICSSWH B respectively. Moreover, the overall reduction in heat loss coefficient between the TD-ICSSWH A and AFRICaS-ICSSWH configurations reached 36.4% and 40.5% for AFRICaS-ICSSWH A and AFRICaS-ICSSWH B respectively. Table *1* summarises the heat transfer coefficients and the thermal resistance as well as the aperture and absorber surface areas (A_{ap} and A_{ab} in m^2) associated by the configured concepts.

The transparent cover on three-quarter of the absorber vessel adds complexity in the AFRICaS-ICSSWH B configuration but produces an improvement of only 2.4% in heat retention efficiency and 6.4% in heat loss coefficient. To reiterate, at the end of the 14-hour monitoring period, AFRICaS-ICSSWH B achieves a temperature difference between the stored hot water and ambient air of 13.3 °C, which is 0.9 K greater than that achieved by AFRICaS-ICSSWH A. The transparent cover is also likely to have an important detrimental impact on the optical efficiency of the AFRICaS-ICSSWH B configuration during the operation mode.

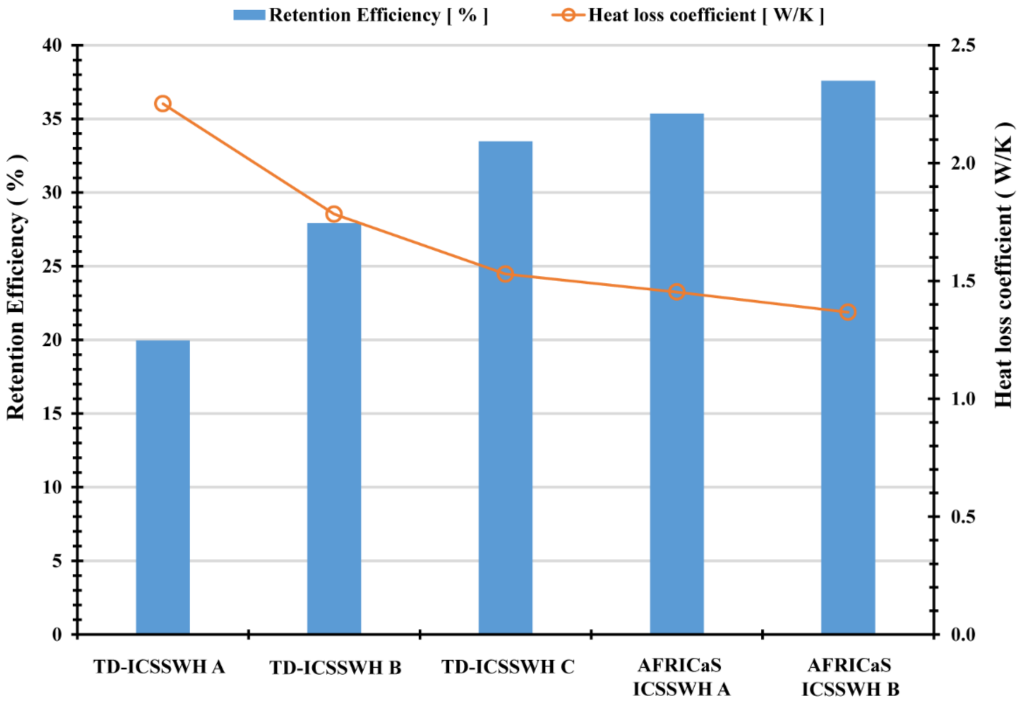


Fig. 7. Heat retention efficiency and heat loss coefficient for a 14-hour period

Table 1
Values of heat loss coefficient during the 14-hour retention period

System	$\mathbf{A_{ap}(m^2)}$	$\mathbf{A_{ab}(m^2)}$	$\boldsymbol{U_L}\mathbf{(W/K)}$	**Thermal Resistance** $\mathbf{(KW^{-1})}$

TD-ICSSWH A	0.63	0.63	2.29	0.44
TD-ICSSWH B	0.63	0.63	1.81	0.55
TD ICSSWH C	0.75	0.63	1.53	0.66
AFRICaS-ICSSWH A	0.52	0.47	1.46	0.69
AFRICaS-ICSSWH B	0.52	0.47	1.36	0.73

Conclusion

Experiments at Ulster University characterised the thermal performance of five variants of Integrated Collector Storage Solar Water Heaters (ICSSWHs) under no draw off operating condition. The ICSSWH system variants comprised of progressive heat loss reduction strategies. The strategies produce an innovative modular Asymmetric Formed Reflector with Integrated Collector and Storage (AFRICaS) system. Experimental results show that retention efficiency of the basic thermal diode ICSSWH (outer aluminium and inner stainless steel concentric cylinder system) increases from 20% to 35% while the heat loss coefficient reduces from 2.29 W/K to 1.46 W/K. After a 14-hour monitoring period, the AFRICaS concept retains hot water at a temperature of 32.6 °C, which is 12.4 °C greater than the prevailing ambient air temperature. By contrast, the basic thermal diode ICSSWH retains hot water at a temperature of 27.1 °C, which is 7.9 °C greater than the prevailing ambient air temperature. Therefore, under the current experimentation mode, the AFRICaS concept has demonstrated superior thermal retention performance. The addition of a transparent cover on three-quarter of the absorber vessel for the AFRICaS-ICSSWH B configuration achieved retention efficiency, heat loss coefficient and retained hot water temperature of 37.6%, 1.36 W/K and 33.4 °C respectively. In comparison, the AFRICaS-ICSSWH A configuration achieved retention efficiency, heat loss coefficient and retained hot water temperature of 35.2%, 1.46 W/K and 32.6 °C respectively. Clearly, the added complexity did not significantly enhance the performance of AFRICaS-ICSSWH A. In addition, the transparent cover could have significant impact on the optical efficiency of system under solar energy collection operating mode. These results represent a situation in which an external heating and circulation device supplies thermal energy into the water contained in the system with no draw off followed by a desired cool down period. Results obtained by operating these systems with no draw off through a heat collection phase such as under a solar simulator or under the sun (outdoor) followed by a cool down phase during the night could differ to some degree. Results also depend upon the effectiveness of the thermal tightness of the insulation materials. Future studies aim to extend the current methodology and to employ standardised experimentation procedures. Although the experimentation mode is atypical of the real situation, the AFRICaS system is a positive step towards the formulation of affordable solar energy technologies that maximise the conversion of locally available solar energy resources. Future studies are to establish technical and economic viability of the novel AFRICaS concept for applications in developing countries.

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Declarations of Interest: none

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