Performance Evaluation of the Senergy Polycarbonate and Asphalt Carbon Nano-Tube Solar Water Heating Collectors for Building Integration

Adrian Pugsley[a,b], Aggelos Zacharopoulos[a], Mervyn Smyth[a], Jayanta Mondol[a]

[a] Ulster University, Centre for Sustainable Technologies, Jordanstown, Northern Ireland www.cst.ulster.ac.uk

[b] Corresponding author: adrianpugsley@gmail.com

Abstract: European Directives 2009/28 and 2010/31 require member states to reduce CO_2 emissions by 20%, increase the share of renewable energy to 20%, achieve energy savings of 20% and mandate that all new buildings must be "nearly zero energy", by 2020. Solar water heating collectors are cost effective and well suited to integration into building envelopes (facades and roofs) to provide heat for direct use inside the building. Senergy building integrated solar collectors are designed to offset traditional roofing elements. Two working prototypes; one Polycarbonate Carbon Nano-Tube (PCNT) collector and one Asphalt Carbon Nano-Tube (ACNT) collector; have been tested at the solar simulator facility at Ulster University and their performances compared. The PCNT collector uses innovative polycarbonate twin-wall sheeting which forms both the solar absorptive surface and the heat transfer fluid channeling elements. The ACNT collector has an asphalt based absorber with embedded serpentine copper tubing to act as the heat transfer fluid channeling element. Tests were conducted with 800 W/m^2 illumination intensity and for water inlet temperatures between from 23°C and 47°C. The PCNT collector achieved 62% maximum collection efficiency compared to 45% for the ACNT collector. The heat loss coefficients were 6.0 and 8.1 W/m^{2}K respectively. The performance of the PCNT collector was similar to benchmark values for single glazed collectors with selective absorber surfaces. The ACNT collector performance was lower than a typical unglazed solar water heater with non-selective absorber due to the high thermal resistance between the absorber surface and the serpentine tubing.

1. Introduction

In 2014, world total primary energy supply was 573 EJ and European OECD countries accounted for 71 EJ of this total (IEA, 2016). Energy produced by these countries amounted to only ~53 EJ of which 78% was from indigenous fossil fuel resources (non-renewable coal, oil and gas) 6% from nuclear power, 8% from biomass and waste, and 5% from hydroelectricity. Energy imports, to make up the shortfall, have economic consequences and represent a risk to the security of the energy supply. Furthermore, millions of years of naturally sequestered carbon stored in fossil fuels is released into the atmosphere when they are processed and combusted, often along with various other pollutant gases. Excessive quantities of anthropomorphic CO_2 and methane appear to be causing global warming and climate change (IPCC, 2015) which is predicted to have serious adverse effects on human society and on biodiversity.

Space heating and Domestic Hot Water (DHW) use in buildings accounts for almost half of all UK energy use and almost three-quarters of all household and commercial energy use (DTI, 2002). Building space heating demands depend upon climatic conditions (ambient temperatures and wind), building fabric construction (thermal insulation and ventilation rates), desired indoor temperatures, heating system efficiency, solar gain and internal gains (occupants, lights, appliances etc). Boardman et al., 2005 suggest that new energy efficient UK homes built in coming decades will have space heating demands of ~2 MWh/year whereas homes built before 1996 typically consume 15 MWh/year. Energy required to produce DHW for a typical household is ~5 MWh/year.

European Directive EU2009/28 aims to reduce CO_2 emissions by 20%, increase the share of renewable energy to 20%, and achieve energy savings of 20% or more by 2020. Directive EU2010/31 requires member states to set minimum energy performance requirements for buildings and mandates that they must be "nearly zero energy" by 2020. These directives require British, Irish and other European buildings to source their energy from renewable sources, ideally via technologies installed on or near to the building. Whilst "Brexit" could feasibly divorce the UK from some of these obligations, the international political consensus (eg the COP21 climate agreement in 2015 to restrict global warming to 2°C) are clear.

Solar thermal (ST) collectors absorb solar energy to generate heat which is typically dissipated from the absorber into a working fluid such as air, water or oil, although in some instances the heat is transferred directly to the end use process. The most common applications for ST systems relate to provision of low temperature hot water (50-80°C) for domestic uses and space heating, or very low temperature hot water (30-50°C) for swimming pools, under floor heating, preheated boiler feedwater or a source for heat pump heating systems.

Data from the Renewable Energy Network for 21st Century (REN21, 2014 and 2016) suggests that global solar thermal collector capacity in 2015 was ~445 GW and appears to be increasing at a rate of ~10% per year. Solar water heaters represent ~98% of the readily quantifiable solar thermal systems installed globally. They are cost effective and well suited to integration into building envelopes (facades and roofs) to provide heat for direct use inside the building. Senergy building integrated solar water heating collectors are designed to offset traditional roofing elements. Two working prototypes; one Polycarbonate Carbon Nano-Tube (PCNT) collector and one Asphalt Carbon Nano-Tube (ACNT) collector; have been tested at the solar simulator facility at Ulster University and their performances compared.

2. Collector design and theory

The working principle of the Senergy solar water heating collectors is essentially similar to other flat plate solar water heaters in that solar radiation incident upon the planar absorbing surface is converted to thermal energy and collected by the heat transfer fluid (Twidell & Weir, 2006; Kalogirou, 2009). The total amount of solar energy incident on each aperture area over the test period can be expressed as:

$$Q_{incident} = I_{ave} A_{ap} \Delta t \qquad \{1\}$$

where:

$$I_{ave} = \left(\int_{t_{end}}^{t_{start}} I(t)\, dt \right) / \Delta t \qquad \{2\}$$

The useful energy gained by the collector is expressed by:

$$Q_{col} = mc_p (T_o - T_i) \qquad \{3\}$$

And thus the heat balance of the system (based on the Hottel-Whillier-Bliss equation for solar collectors) that expresses the thermal performance of a collector under steady state conditions is given by:

$$\mathrm{mc_p}\left(\mathrm{T_{out}} - \mathrm{T_{in}}\right) = \mathrm{A_{ap}} F_R \left[I_{ave}(\tau\alpha) - U_L \left(T_{out} - T_{in}\right)\right] \qquad \{4\}$$

Therefore the collector efficiency is defined as:

$$\eta_{\mathrm{col}} = \frac{\mathrm{mc_p}\left(\mathrm{T_{out}} - \mathrm{T_{in}}\right)}{\mathrm{I_{ave} A_{ap}}} \qquad \{5\}$$

Or substituting Equation 4:

$$\eta_{\mathrm{col}} = F_R(\tau\alpha) - F_R U_L \frac{\left(\mathrm{T_{in}} - \mathrm{T_{amb}}\right)}{\mathrm{I_{ave}}} \qquad \{6\}$$

The key novelty is that the Senergy collectors incorporate carbon nanotubes to increase collection efficiency in two ways: 1) By improving the solar absorption and emittance characteristics making absorber surfaces partially spectrally selective, and; 2) By improving thermal conductivity between the absorber surface and the heat transfer fluid. A photograph of the two collectors examined in this study is given in Figure 1.

Figure 1: Senergy PCNT (left) and ACNT (right) solar water heating collectors

The PCNT collector design is based upon the novel use of polycarbonate twin-wall sheeting to create the solar absorptive surface and heat transfer fluid channeling elements. The prototype was made from extruded polycarbonate twin-wall that was understood to contain 2% carbon nanotubes. The twin-wall polycarbonate unit was connected to a flow and return manifold and mounted in an insulated wooden tray base. A single transparent polycarbonate layer provided aperture protection. The finished active absorbing surface of the collector was 1480 x 500mm.

The ACNT collector design is based upon a simple and robust concept of using asphalt to create the solar absorptive surface. A serpentine coil of copper tubing is embedded within the asphalt to act as the heat transfer fluid channeling element. The prototype was made from asphalt that was understood to contain carbon nanotubes. The asphalt was set into a wooden tray base and was uncovered. The finished active absorbing surface of the collector was 1605 x 600mmm.

3. Experimental methodology

All testing was conducted at the state-of-the-art indoor solar simulator facility at the Centre for Sustainable Technologies laboratory, Ulster University. The experimental set up consisted of prototype collectors connected to a heating/cooling loop via the Julabo F33-MA Refrigerated/Heating Circulator that could provide a closed flow circuit under constant, controllable conditions. The experimental set up is schematically shown in Figure 2.

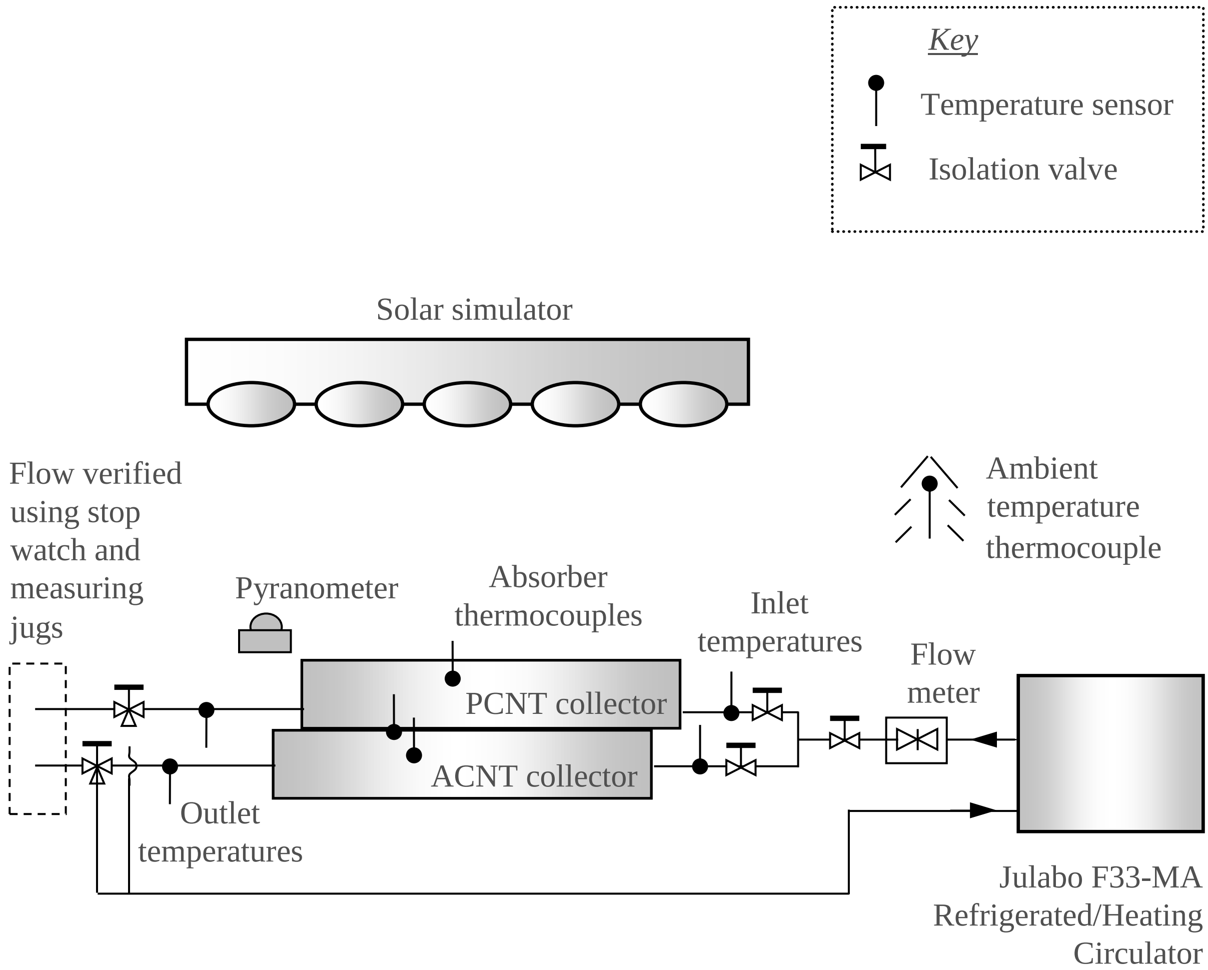

Figure 2: Schematic detail of test facility and instrumentation (two collectors, side by side)

Pairs of T-type copper-constantan thermocouples, which had an error of ±0.5°C between 0°C and 70°C were used to measure the temperature of solar collector inlet and outlet flows, the absorber surface temperature and the ambient air temperature. The collectors were each supplied with three thermocouples located at the inlet end, middle, and outlet ends of the units. Thermocouples supplied with the PCNT collector were attached to the absorber in order to measure absorber surface temperature. Thermocouples supplied with the ACNT collector were embedded within the asphalt to measure absorber core temperature. In addition, two further thermocouples were installed on the asphalt surface of the ACNT collector in order to determine absorber surface temperature. All thermocouples were connected to a stand-alone Delta-T data logger unit to record all measured variables. The logger data was transferred to a PC via a data transmission cable for storage. Manual gravimetric flow meters were employed to monitor water flow rate in the collector heating/cooling loop. The flow through each of the collectors was checked periodically using measuring jugs and a stopwatch to verify the amount of water flowing through each collector during a three-minute period.

All tests were conducted under a constant 800 Wm^{-2} solar flux simulated by a state-of-the-art solar simulator. The simulator lamp array consists of high power 35 metal halide lamps arranged in 7 rows of 5 lamps each. Each lamp is equipped with a rotation symmetrical paraboloidal reflector to provide a light beam of high collimation. In order to achieve uniform distribution of light intensity on the test area, a lens is inserted in each lamp to widen the illumination of light. The combination of reflector-characteristics, lens and lamps ensures a realistic simulation of the beam path, spectrum and uniformity (Zacharopoulos et al., 2009). Tests were undertaken simultaneously on both the PCNT and ACNT collectors under the following controlled conditions:

i) Irradiance, temperature, air and water flow conditions were set to be broadly comparable to those required for testing under BS EN 12975-2 (2006) 'Thermal solar systems and components solar collectors - Part 2', although the tests were not undertaken in strict accordance with the standard.

ii) Solar simulated irradiance level (average across each collector) of 800 ± 5 Wm^{-2}. Pyranometer measurements at different points across the surfaces of the two collectors suggested variation in intensity of no more than ±50 Wm^{-2}.

iii) Flow rates of 0.02 $kg.s^{-1}m^{-2}$ were maintained through each collector during tests, except for stagnation tests. Measured flow rates through the PCNT and ACNT collectors were 0.99±0.2 litres/minute and 1.31±0.3 litres/minute, respectively, corresponding to the respective absorber areas of 0.74 m^2 and 0.96 m^2.

iv) Water supply temperatures at the collector inlets were varied from 23°C (equal to ambient temperature) in steps of either 4°C to 5°C up to a final temperature of 47°C.

v) Airflow at ambient temperature was provided across the surfaces of the collectors in the direction from outlet towards inlet.

vi) Stagnation tests were undertaken to estimate the maximum absorber surface temperature reached by each collector in the absence of water flow.

The test setup was operated for 2½ hours prior to taking any measurements in order to allow for stabilisation of the irradiance levels, ambient temperatures and the initial thermal mass of the ACNT collector. Further stabilisation periods (typically about 30 minutes per temperature step) were factored into the test programme to ensure that all step measurements would be representative of steady state conditions.

4. Results and discussion

Figures 3 and 4 illustrate the inlet, outlet, absorber and ambient temperatures measured for both collectors, based on arithmetic averages of results from the thermocouple pairs. Step changes to the inlet water temperature are apparent, together with the subsequent stabilisation periods.

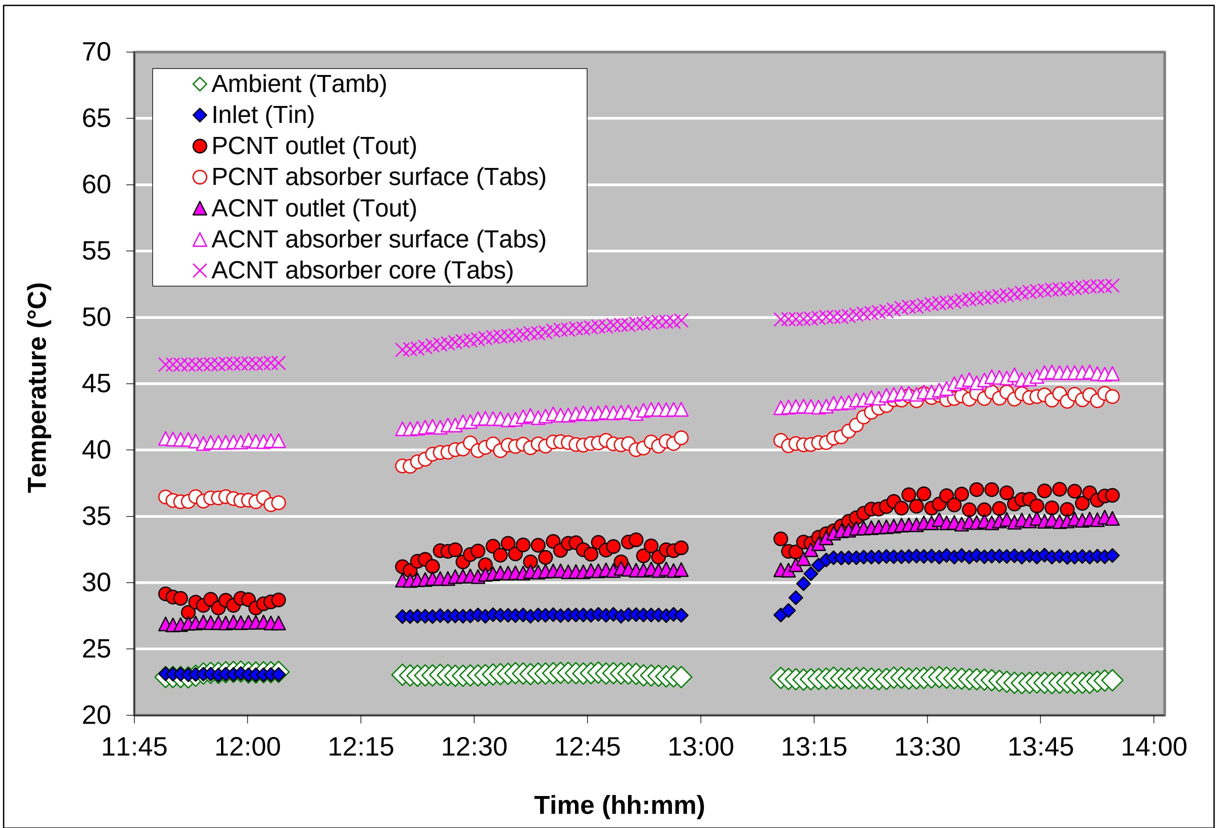

Figure 3: Measured inlet, outlet, absorber and ambient temperatures for both collectors under lowest inlet temperature conditions

Unfortunately, a leak occurred in the PCNT collector sometime after 16:30 (Figure 4) so results corresponding to inlet water temperature of 47°C are unreliable for this collector due to the disrupted flow rate. After 16:45 the collectors were largely emptied of water and the subsequent data therefore relates to a stagnation condition, characterised by a rapid rise in absorber temperatures (particularly apparent for PCNT collector data denoted by red dashed lines on Figure 4). Problems caused by the leaking collector meant that the experiment was terminated prior to steady-state stagnation conditions being achieved and hence estimated stagnation temperatures shown on the graphs are based on observed trends.

The comparatively low rate of temperature change for the ACNT collector comparted to the PCNT collector is indicative of the large thermal mass associated with the asphalt absorber. This results in a very slow response to changes in inlet water temperature. A similarly slow response would be expected to changes in solar irradiation conditions which may result in a poor diurnal performance, especially in climates typified by intermittent cloud cover. Whilst a degree of thermal inertia can be beneficial, the current design appears to carry excessive mass.

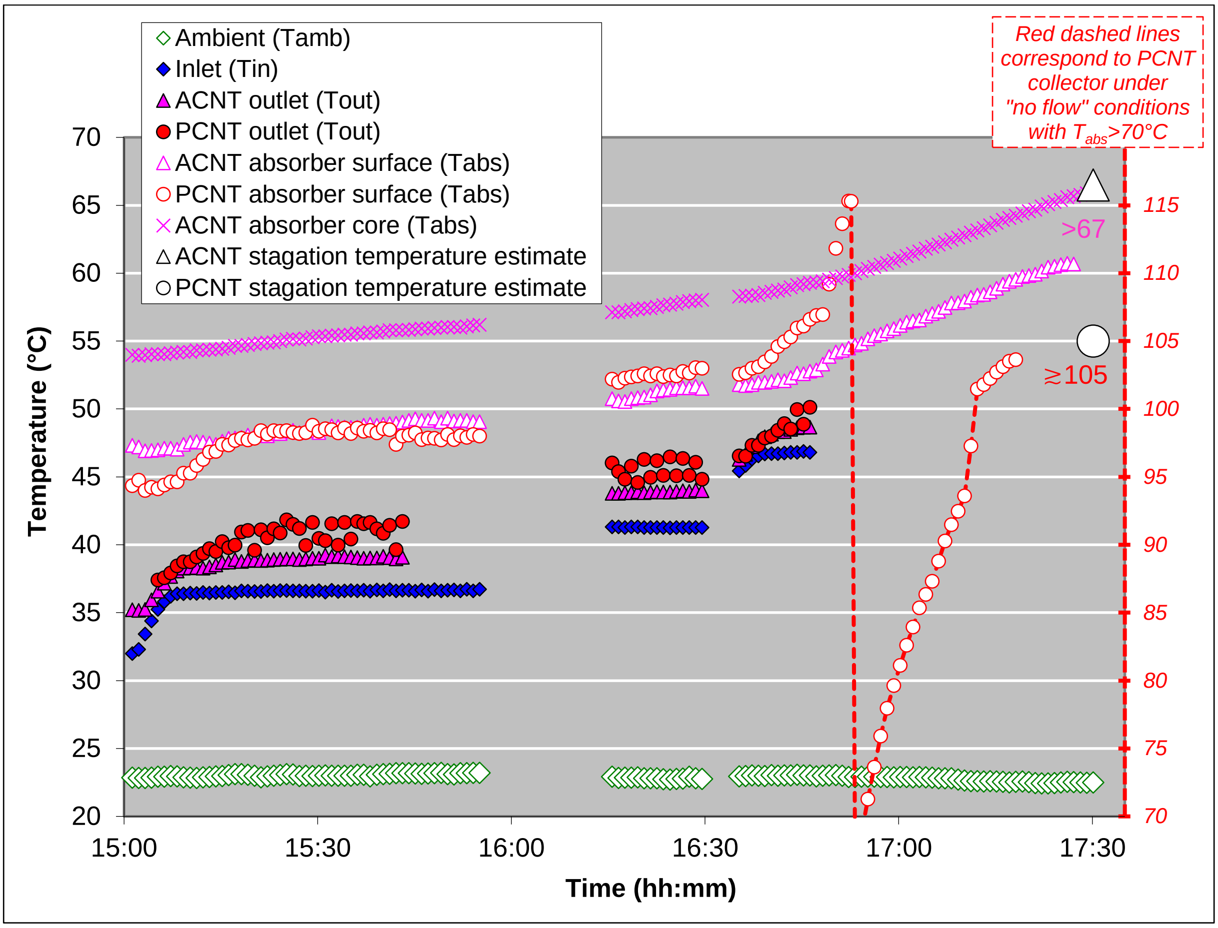

Figure 4: Measured inlet, outlet, absorber and ambient temperatures for both collectors under highest inlet temperature conditions

Using Equations 1 to 6, the solar thermal collection efficiencies of the prototypes were determined (Figure 5) for a variety of operating conditions and compared with published benchmark performances for typical solar water heating collector types. The benchmark performances for unglazed, single glazed and double glazed flat plate collectors, along with evacuated tube collectors, were determined from data presented by Twidell & Weir, 2006; Kalogirou, 2009; Liang et al. 2011; and Giovannetti et al. 2014.

The measured zero temperature rise efficiencies (the $F_R(\tau\alpha)$ value apparent from the y-axis intercepts on Figure 5) of the PCNT and ACNT collectors are similar to the benchmark for evacuated tube collectors but considerably lower than achieved by most other flat plate collectors. The ACNT collector appeared to have reasonably good light absorption characteristics (black bitumen absorber surface with a slight sheen) and is unlikely to have suffered from significant reflection losses (as it was unglazed) which suggests that the low measured efficiency (45% compared to 90% for the unglazed collector benchmark) is primarily attributable to a low heat removal factor. The relatively low measured efficiency for the PCNT collector (62% compared to 83% for the single glazed matt black collector) may also be partially attributable to a low heat removal factor, although optical losses (absorber and cover reflectivity and low optical transmissivity of the semi-translucent cover) seem likely to be the more significant causes. Absorbers made of polymeric materials often have lower heat removal factors than conventional metal sheet-and-tube absorbers owing to inherently lower thermal conductivities. The very low apparent heat removal factor for the ACNT is likely to be caused by the heat exchanger pipework being buried too deep within the asphalt and perhaps also by the pipe length being too short, which introduce very high thermal resistances between the absorber and the working fluid. This is evidenced by the significant difference (10 to 20°C) between the ACNT's core and outlet temperatures and the 5 to 7°C temperature difference between the core and absorber surface temperatures.

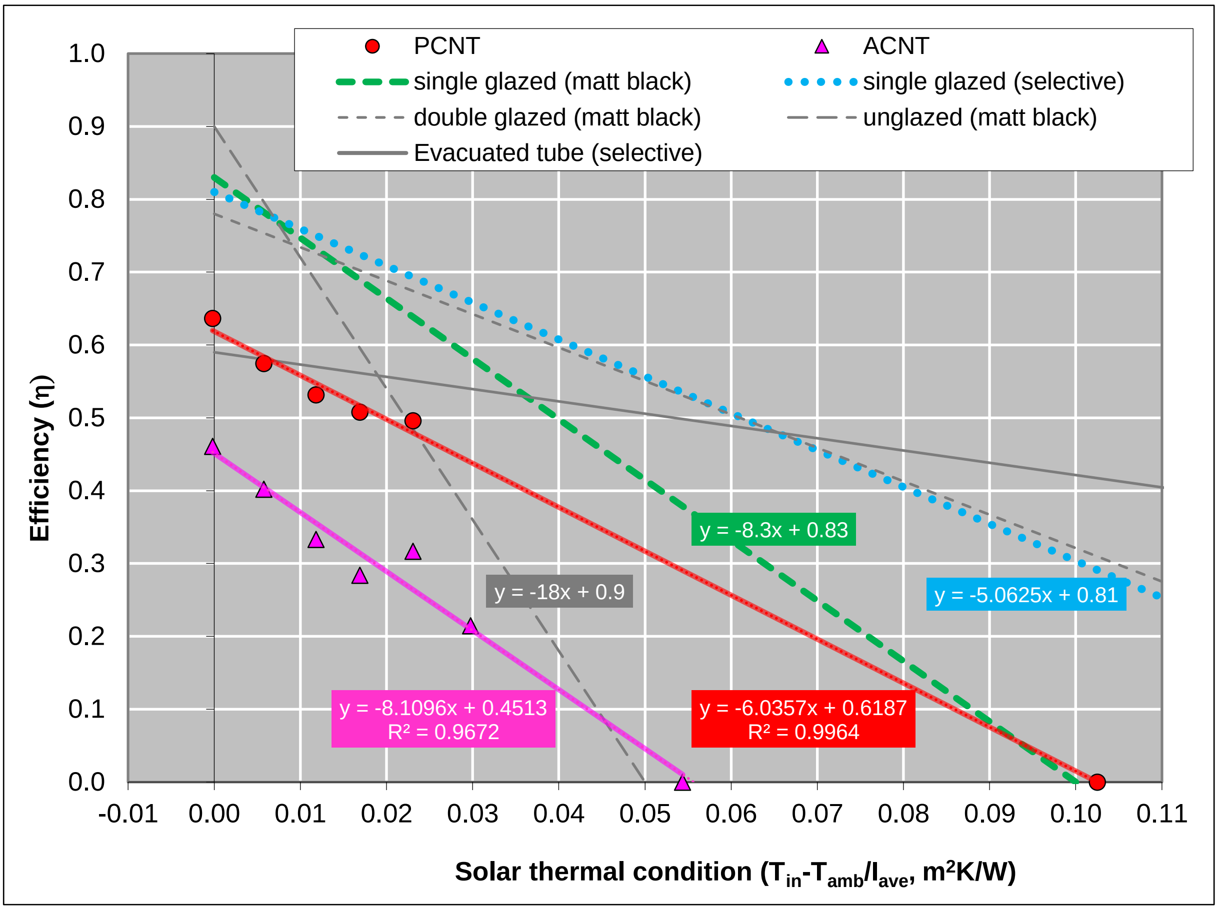

Figure 5: Comparison of instantaneous efficiency of Senergy solar water heater prototypes against other flat plate solar collector benchmarks

The thermal insulation performances (the F_RU_L values apparent from the trendline gradients on Figure 5) of the prototype collectors are considerably lower (better) than the corresponding benchmarks. The ACNT achieved a heat loss coefficient of 8.1 W/m^{2}K which is less than half the unglazed collector benchmark value (18 W/m^{2}K). The PCNT achieved a heat loss coefficient of 6.0 W/m^{2}K which is 28% lower than the benchmark value for single glazed collectors with matt black absorbers (8.3 W/m^{2}K) and approaches the benchmark value of 5 W/m^{2}K for single glazed collectors with selective absorbers (high absorptivity and low emissivity). The cause of the low heat loss coefficients cannot be reliably determined from the test data but is thought to be primarily due to the low heat removal factor. The degree to which the carbon nanotubes increase thermal conductivity and affect the optical properties of the absorber surfaces will be determined through further testing as part of the ongoing research.

5. Conclusions

The performance of the Senergy polycarbonate (PCNT) and asphalt (ACNT) carbon nanotube solar water heating collectors was investigated under controlled simulated conditions. The single glazed PCNT collector achieved higher collection efficiencies than the unglazed ACNT collector under all tested conditions. Test results have been compared to published benchmark performances for flat plate and evacuated tube solar water heaters. Both collectors achieved measured zero temperature rise efficiencies (45% for ACNT and 62% for PCNT) of similar magnitude to the benchmark for evacuated tube collectors. The measured heat loss coefficient for the ACNT collector (8.1 W/m^2K) is significantly better than the benchmark for an unglazed collector. The measured heat loss coefficient for the PCNT collector (6.0 W/m^2K) is equivalent to that achieved by a conventional one-cover liquid heater with moderately selective absorber. The ACNT collector had a very slow thermal response rate due to its high thermal mass and a very low heat removal factor due to high thermal resistances within the asphalt absorber. The degree to which the carbon nanotubes increase thermal conductivity and affect the optical properties of the ACNT and PCNT absorber surfaces will be determined through further testing as part of the ongoing research.

6. Nomenclature

α	(dimensionless)	Solar absorption coefficient
A_{ap}	(m^2)	Collector aperture area
c_p	($J.kg^{-1}K^{-1}$)	Specific heat capacity of the working fluid
F_R	(dimensionless)	Heat removal factor
η_{col}	(dimensionless)	Solar thermal collection efficiency
I_{ave}	($W.m^{-2}$)	Instantaneous solar radiation flux incident on collector aperture
m	($kg.s^{-1}$)	Working fluid mass flow rate
Q_{col}	(J)	Thermal energy collected by the working fluid
$Q_{incident}$	(J)	Total solar energy incident on collector aperture area
t	(s)	Time
Δt	(s)	Duration of the test period
T_{abs}	(°C)	Temperature of the solar absorber surface
T_{amb}	(°C)	Temperature of the ambient environment near the collector
T_{in}	(°C)	Working fluid temperature at the collector inlet
T_{out}	(°C)	Working fluid temperature at the collector outlet
τ	(dimensionless)	Solar transmission coefficient
U_L	($Wm^{-2}K^{-1}$)	Heat loss coefficient which quantifies the thermal conductance between the working fluid bulk and the ambient environment

7. References

Boardman, B., Darby, S., Killip, G., Hinnells, M., Jardine, C., Palmer, J., Sinden, G. (2005). 40% House. ISBN-1-874370-39-7. University of Oxford, UK, Environmental Change Institute. Available at: <http://www.eci.ox.ac.uk/research/energy/downloads/40house/40house.pdf>

BS EN 12975-2 (2006). Thermal solar systems and components solar collectors - Part 2. London, UK: British Standards Institute.

DTI - Department of Trade and Industry (2002). Energy consumption in the United Kingdom. London, UK: HM Government.

European Union (EU) Directive 2009/28/EC on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC. Official Journal of the European Union.

European Union (EU) Directive 2010/31/EC on the energy performance of buildings (recast). Official Journal of the European Union.

Giovannetti, F., Foste, S., Ehrmann, N., Rockendorf, G. (2014). High transmittance, low emissivity glass covers for flat plate collectors: Applications and performance. Solar Energy 104 (2014) 52–59.

IEA – International Energy Agency (2016). Key World Energy Statistics 2016. Paris, France: IEA. Available at: <https://www.iea.org/publications/freepublications/publication/key-world-energy-statistics.html>

IPCC – Intergovernmental Panel on Climate Change (2015). Climate Change Report 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva, Switzerland: IPCC. ISBN 978-92-9169-143-2

Kalogirou, S. (2009). Solar energy engineering. London: Academic Press (Elsevier) ISBN 13: 978-0-12-374501-9

Liang, R., Ma, M., Zhang, J., Zhao, D. (2011). Theoretical and experimental investigation of the filled-type evacuated tube solar collector with U tube. Solar Energy 85 (2011) 1735–1744.

REN21 (2014). Renewables 2014 Global Status Report. Paris, France: Renewable Energy Policy Network for the 21st Century (REN21) Secretariat. ISBN 978-3-9815934-2-6

REN21 (2016). Renewables 2016 Global Status Report. Paris, France: Renewable Energy Policy Network for the 21st Century (REN21) Secretariat. ISBN 978-3-9818107-0-7

Twidell, J. and Weir, T. (2006). Renewable Energy Resources (2nd ed.) London: Taylor Francis. ISBN13:9-78-0-419-25330-3Zacharopoulos, A., Mondol, J., Smyth, M., Hyde, T., O'Brien, V. (2009). State of the Art Solar Simulator with Flexible Mounting. Proceedings ISES Solar World Congress, 11-14 October 2009, Johannesburg, South Africa, pp 854-863