A DOMESTIC SOLAR WATER HEATER TESTING FACILITY FOR SOUTHERN AFRICA

Andrew L. de Wet[1] and Paul Gauché[2]

[1] BEng (Mech), Research and Test Engineer STERG, Dept. Mechanical and Mechatronic Engineering, Stellenbosch University, Private Bag X1, Matieland,7602, South Africa, Phone: +27 21 808 4226, E-Mail: aldewet@sun.ac.za.

[2] MEng (Mech), Sr. Researcher and Coordinator STERG, Dept. Mechanical and Mechatronic Engineering, Stellenbosch University

Abstract

The Department of Mechanical and Mechatronic (M&M) Engineering at Stellenbosch University (SU) recently upgraded facilities to carry out performance and R&D testing of domestic solar water heater (DSWH) systems for the South African market using an outdoor test method. The state of facilities and initial verification test results are provided with recommendations on further improvements to be made.

Keywords: Domestic solar water heater, Test facility.

1. Introduction

The Solar Thermal Energy Research Group (STERG) of SU obtained funding from the Austrian Development Agency through the AEE INTEC SOLTRAIN training project to deploy a facility capable of executing performance testing of DSWH systems for the commercial sector. The need for a testing facility was identified after increased R&D support requests from industry and the lack of quality testing equipment at STERG's disposal. The only other DSWH testing facility available to the Southern African commercial sector is the Pretoria based South African Bureau of Standards (SABS). Free testing for the first five clients (SOLTRAIN trainees) is to be provided.

2. Objective

The grant was about an order lower than typically required to construct such a facility [1]. STERG set the goal to design and install a facility of comparative features at a much lower cost. The SABS certification facility mainly performs specific tests and the purpose of the STERG facility is to cater for performance and R&D testing based on individual client requirements. The facility is also to support undergraduate and postgraduate SU students as an educational step to solar thermal energy careers.

3. Review of Policies and Available Infrastructure and Standards

The available infrastructure was evaluated to determine the upgrade potential. Experience in DSWH testing by STERG augmented by available standards were consulted to determine testing requirements..

3.1. The Solar Roof Laboratory

A dedicated location for the facility was assigned on the open-air Solar Roof Laboratory (SRL). The 28 x 13 m SRL is housed on the second level roof with a control room on the third level looking out onto the roof area. Refer to Fig. 1 for an overall view of the Solar Roof Laboratory.

3.2. Environmental and Departmental Guidelines

The SRL is a harsh environment with the the presence of sunlight, rain and dust particulate. A minimum ingress protection (IP) rating of IP54 is required, with IP65 preferred. UV-stabilized materials are mandatory. M&M departmental policy requires that a hot water supply is limited to 60 °C to prevent scalding. National support of hardware and software is preferred. M&M department best practice guidelines for temperature measurements advises the use of two temperature probes at the point of interest to indicate probe failure.

Fig. 1. Overall view of the Solar Roof Laboratory from the North.

3.3. Available Testing Standards

The national standard by the SABS for determining the thermal performance of domestic solar water heaters using an outdoor test method, SANS 6211-1:2003 [2], was consulted. The standard describes a basic and advanced (long-term energy output) thermal performance test. Both tests entail a single hot water draw-off at 10 L/min in the evening to determine the thermal performance of a complete DSWH system where the degree of mixing in the tank during draw off and overnight heat-loss is evaluated. This standard was previously used most often for DSWH testing at the M&M department with limited equipment. A schematic presentation of an installation for thermal performance testing is provided in Fig. 2.

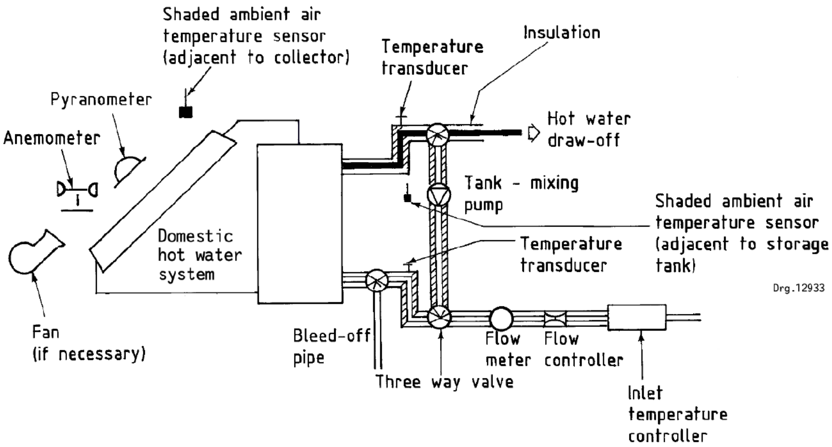

Fig. 2. Schematic of a thermal performance test installation from SANS 6211-1:2003 [2].

The DIN EN 12975-2:2006-06 [3] standard describes test methods for solar collectors, of which only the performance section was consulted. The collector efficiency is determined by testing the collector energy output at a constant mass-flow rate and under clear skies. The fluid inlet temperature is changed to obtain at least four data points across the collector operating range. The maximum water inlet temperature must be at least 80 °C, which is above M&M departmental regulations. The collector efficiency is described by $\eta = \eta_0 - a_1\, T_m{}^* - a_2\, G\, (T_m{}^*)^2 = \left[\dot{m}\, c_f\, (T_{out} - T_{in})\right]/(A\, G)$ and the reduced temperature difference $T_m{}^* = [(T_{in} + T_{out})/2 - \mathrm{T_{amb}}]/G$. For further details, refer to [3].

4. Testing Requirements

The following project requirements were set:

• A pumped water reticulation system is required to have a controlled water source and to conserve water. The water supply temperature must be limited to 60 °C and at a constant pressure, adjustable from 2.5 to 4 bar. Supply plumbing and equipment must withstand water at 90 °C for future collector efficiency testing.

• Data loggers and analogue controllers with an adequate personal computer to use during testing is required. The logging solution must be remotely operable, independent of the pumped reticulation control system and housed in an enclosure suitable for the SRL environment.

• A universal communications network between the logging solution, pump reticulation control system and the SRL is required.

• Flow meters and flow control valves suitable for DSWH testing are required. Sizing of the flow meters and control valves should be based on [2], requiring a flow rate of 10 L/min and measurement accuracy of ±3%.

• Frames for mounting any domestic collector at any angle and any water storage cylinder at any reasonable height and orientation are required. Limit the tank volume to 300 L to reduce the load on the SRL floor.

• Additional solar resource and weather measurement equipment is required.

• The facility should be able to accommodate three DSWH installations of which one will house a reference collector (with a known efficiency curve) and hot water cylinder. The other two stands are for client comparative testing and results can be compared with the reference system.

5. Design

The methodology followed during the design process to minimise the project cost is presented in this section.

5.1. Water Reticulation System

The concept design of the reticulation system converged onto the diagram shown in Fig. 3, which is summarised as a closed loop pumped circuit which vents to atmosphere. Venting to atmosphere results in the possibility of steam as the water temperature approaches 100 °C.

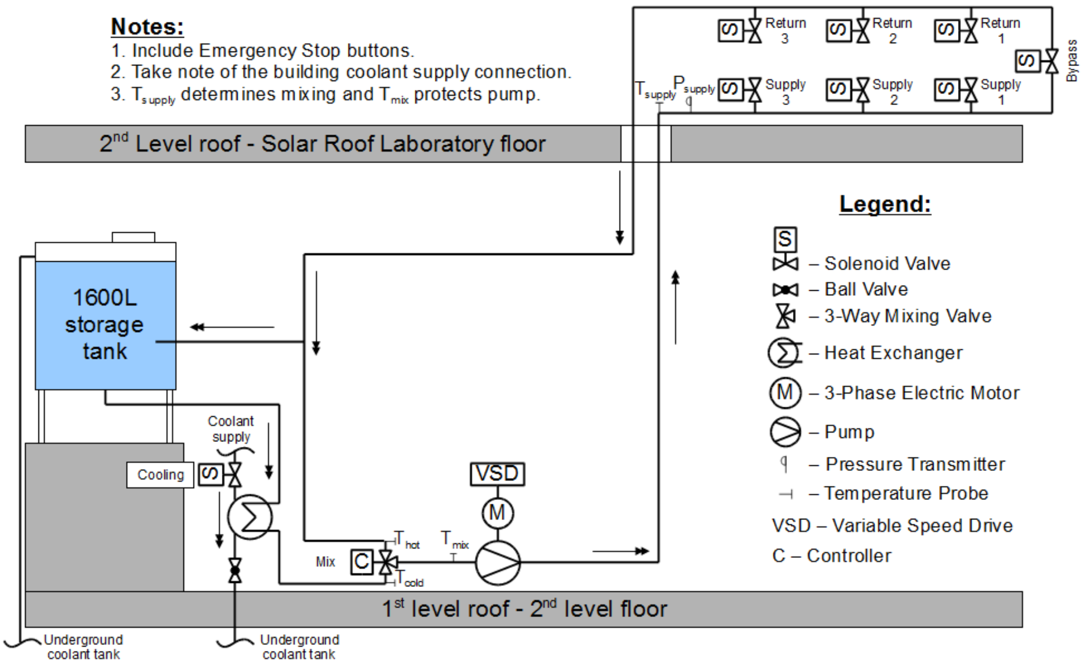

Fig. 3. Water reticulation pump and plumbing schematic.

A stand-alone programmable logic controller (PLC) was selected to control the reticulation system due to the required level of safety, automation and independence of the logger solution. Safety is insured with an emergency stops at the pump, control room and the far end of the SRL. Activation of an emergency stop brings the pump to a standstill and closes all of the solenoid valves.

The pump was specified first and is situated one floor lower than the laboratory to be close to the building coolant supply, hence the additional 4 m height was factored into the pump decision. The vertical 6-stage centrifugal pump with a 3-phase motor can supply a single stand or all three stands simultaneously with water at the required volume flow rate and head (thus 600 to 1800 L/h at 2.5 to 4 bar) by varying the voltage supply frequency using a variable speed drive (VSD). The VSD is controlled by the PLC with feedback from a pressure transmitter installed on the supply plumbing in the control room.

Water needed for testing is stored in a sufficiently large storage tank. The 1600 L stainless steel 304 tank can supply three 300 L hot water cylinders of water simultaneously, with a 700 L reserve to fill the plumbing and collectors and to serve as a cold water buffer.

Hot water is obtained from the test stands with no auxiliary heating applied. The PLC controlled 3-way mixing valve mixes return hot water and cold water from the brazed plate heat exchanger (HX) before feeding it to the pump. The HX is sized to supply 20 °C water for the case where all three stands are supplying 90 °C water at 10 L/min. The HX cools by using water from the building coolant supply, isolated by a PLC operated normally closed (NC) coolant solenoid valve. Refer to Fig. 4 for a photo of the installed tank, pump, mixing valve and heat exchanger.

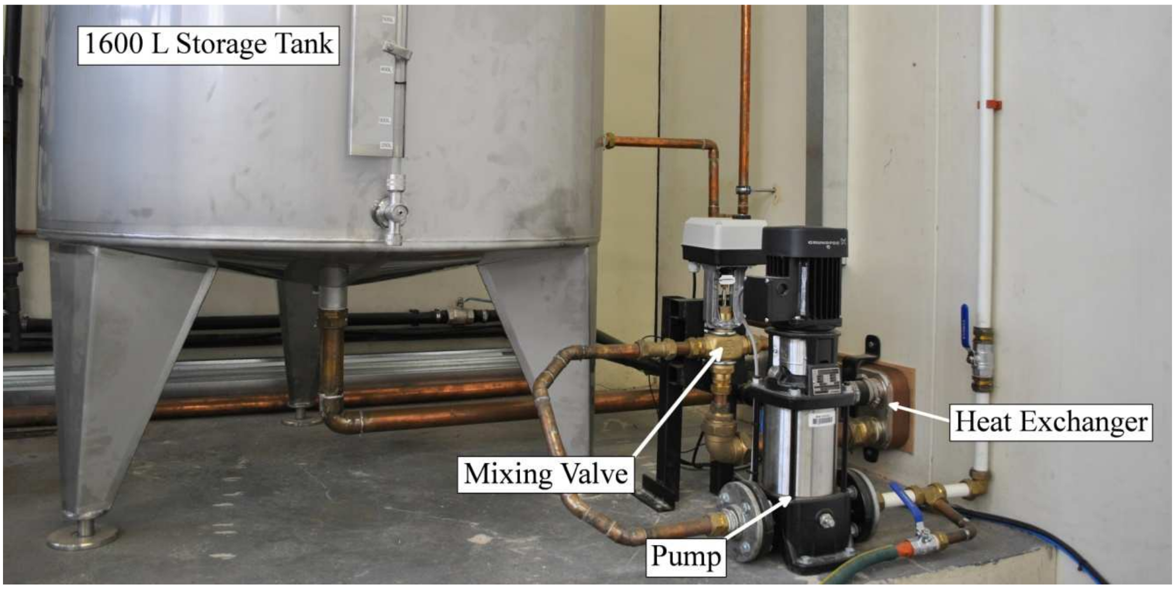

Fig. 4. Reticulation system tank, pump, mixing valve and heat exchanger.

Multi-layer-piping (MLP) was used for the supply plumbing as it has zero scrap value, which is considered beneficial with the level of copper pipe theft in South Africa. The white MLP has a maximum temperature rating of 93 °C and exhibits some thermal insulation properties with a thermal conduction coefficient of 0.43 W/m·K. To safely operate at higher water return temperatures (with the possibility of steam at 110 °C), copper piping was used with capillary solder copper fittings to reduce cost.

Water to and from the stands are isolated by three pairs of PLC controlled high temperature NC solenoid valves which are fastened to the wall to decrease the weight on the plumbing and ease test installation. A high temperature NC bypass solenoid valve at the far end of the loop links the supply and return plumbing in order to reach a steady state water supply temperature before testing. Compressed air at 6 bar required by the flow control valves is isolated by a PLC controlled NC solenoid valve.

The complete Allen-Bradley PLC system was designed and assembled by STERG. A MicroLogix 1400 PLC forms the base of the system providing digital outputs for the various solenoid valves, digital inputs for the emergency stops and a 0-10 V signal to control the VSD. A 4-channel RTD (1762-IR4) expansion module is installed for temperature measurement of the water supply using Pt100s. A 2-channel 0-20 mA output, 2-channel 0-20 mA input expansion module (1762-IF2OF2) is included to measure the pressure transmitter signal and control the linear actuator of the three-way mixing valve. The PLC system is controllable via Ethernet by a PanelView C600 colour human-machine interface (HMI) housed in a stainless steel 304 enclosure with an independent 24 VDC power supply. The portable HMI enables the user to control the reticulation system from the SRL or control room. Refer to Fig. 5 for an overall view of the PLC system.

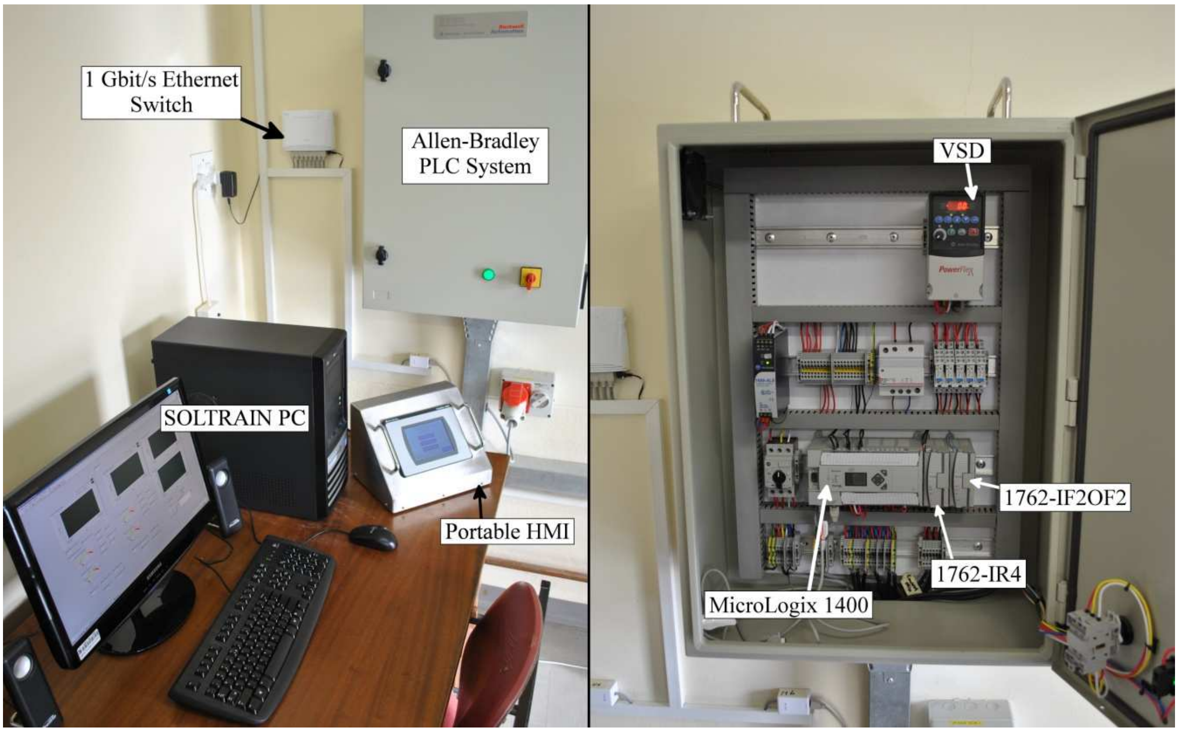

Fig. 5. Overall view of the control station and PLC system

5.2. Data Logging and Control

National Instruments (NI) products provide a single modular solution in the form of the CompactDAQ 9188 chassis. The chassis can accommodate 8 modules whilst communicating with and logging to a personal computer via Ethernet. STERG has access to NI's LabVIEW™ programming utility, of which the level of automation enables water usage profiles to be tested for simulation verification.

Experience in previous DSWH testing led to the choice of T-type thermocouples for temperature measurements. T-type thermocouples are typically less expensive than Pt100 probes, with NI thermocouple modules offering more channels than the Pt100 modules for similar cost. Analogue input and output signals between the NI chassis, flow control valves and flow meters were standardise to 4-20 mA. The decision was based above 0-10 V signals due to resistance to electromagnetic interference and the distance the signal might need to travel on the SRL.

Six versatile NI 9213 16-channel, 24-bit thermocouple modules provide sufficient channels for the testing facility. For collector and cylinder configuration testing, 93 thermocouple channels are anticipated when factoring in two thermocouples per measurement and a channel for the pyranometer. The flow control valves accept a 4-20 mA input signal (set valve position) with a 4-20 mA output signal (valve position feedback). The flow meters produce a 4-20 mA output signal and the anemometer modulates a 4-20 mA output signal to indicate the wind speed. A 4-channel NI 9265 module producing 16-bit, 0-20 mA output signals and a 24-bit NI 9207 input module accommodates the analogue requirements. The NI 9207 comprises 8 channels of ±20 mA and 8 channels of ±10 V input signals.

The NI logger solution was assembled in a weatherproof enclosure, pictured in Fig. 6, with a 24 VDC, 5 A power supply to provide power to the flow control valves, flow meters, anemometer and additional equipment on the SRL requiring 24 VDC during testing. The logger enclosure is equipped with a fixed power cord and Cat5e Ethernet cord of 10 m long each to enable remote placement on the SRL.

5.3. Physical Infrastructure and Equipment

Electromagnetic flow meters measure the volumetric flow rate at each test stand. The flow meter insertion fittings were sized for 10 L/min with an orifice nominal diameter of 15 mm. This provides for higher flow rates during future projects. Additional insertion fittings with an orifice nominal diameter of 6 mm are

Fig. 7. Weatherproof logger enclosure

adequate for collector efficiency testing. This is sized for a maximum flow rate of 5 L/min if the entire 4m^2 collector platform undergoes testing according to [3] (a mass-flow rate of 0.02 kg/s/m^2 collector aperture area). Angle seat flow control valves and pneumatic continuous positioners control the flow rate of each test stand. Sizing based on 10 L/min resulted in an orifice diameter of 13 mm, which is in the lower operating range of the valves. Three manually operated integral bonnet needle valves with a 4.4 mm orifice and regulating stem serve for collector efficiency testing. Fig. 7 shows an angle seat valve and flow meter.

Fig. 7. Angle seat valve (a) and electromagnetic flow meter (b)

Three sets of test frames were designed and manufactured in-house to separately house collectors and cylinders. The collector frames include grid platforms of 2 x 2 m to accommodate different collector designs, adjustable from 0° to 90°. The cylinder frames can accommodate different cylinder designs with minimalist manufacturing of custom brackets. Thermo siphon and pumped setup cylinder elevations are possible.

Weather measuring equipment is supplemented by a Kipp & Zonen CMP 6 pyranometer, a six-plate radiation shield for ambient air temperature thermocouples and an R.M. Young Wind Sentry anemometer. A 1 Gbit/s Ethernet network spans the control room and SRL, servicing the computer, portable HMI, PLC system and logger solution. The reference flat plate collector model has been tested using an indoor solar simulator [4]. The collector's single 0.3 mm thick aluminium sheet is covered by a highly selective vacuum coating, with 22 mm copper header pipes and 12 parallel 8mm copper riser pipes. The total aperture area is 2.238 m^2.

6. Initial Verification Test Results

Benchmark testing of the facility include confirming the reference collector efficiency curve. Initial test results are reasonably promising, but reveal limitations due to the maximum achievable inlet temperature (25 °C above ambient) without auxiliary heating. The limitations indicate further improvements to be made to the system. Present benchmark results are shown in Fig. 8. The stagnation point is obtained by stopping the flow of water at the correct time of day to avoid steam forming in the collector. Fig. 9 depicts the reference collector and the second client installation undergoing testing to obtain the collector efficiency curves.

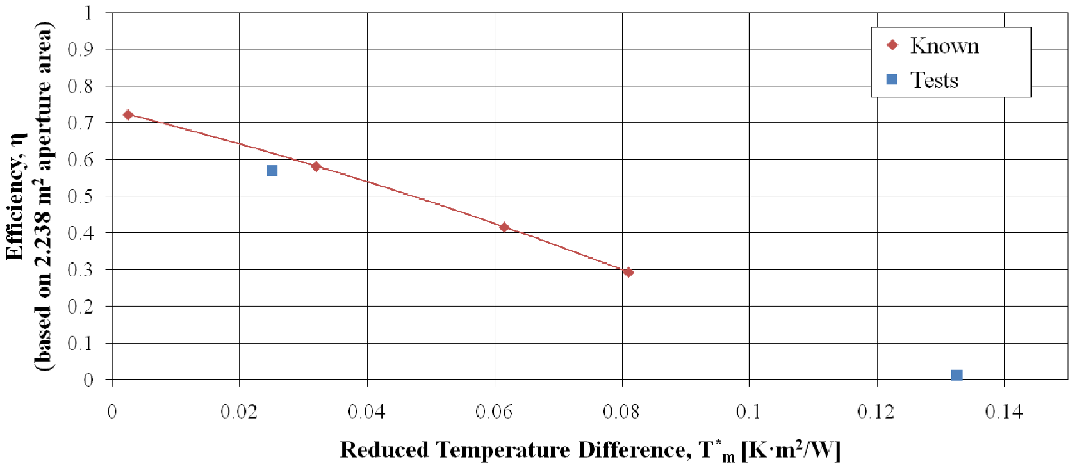

Fig. 8. Reference collector efficiency curve

Fig. 9. The reference and client collectors undergoing testing

7. Comparisons Between the Facility and Standards

Comparisons between the current technological state of the facility and minimum requirements of the consulted standards are presented in Table 1.

Instrumentation	Facility	[2]	[3]
$\dot{m}$ measurement accuracy of measured value (MV)	4 %	3 %	1 %
T_{in} and (T_{amb}) measurement accuracy	0.5 K (0.5 K)	0.1 K (0.5 K)	0.1 K (0.5 K)
$(T_{out} - T_{in})$ measurement accuracy	0.5 K	-	0.05 K
T measurement resolution	0.02 K	0.1 K	0.02 K
Pyranometer classification (according to WMO)	First class	First class	First class
Air velocity measurement accuracy	±0.5 m/s	0.5 m/s	0.5 m/s

Analogue output signal error from integrators	< 1 % of MV	1 % of MV	1 % of MV
Analogue data logger input signal error of full scale	±0.05 %	±0.5 %	0.5 %
Data logger time constant	≤ 1 s	≤ 1 s	≤ 1 s

Table 1. Comparison of facility technological state against consulted standards

The flow meter accuracy is ±4% of MV using the standard K factors provided by the manufacturer, with improvements to ±2% by performing a "teach-in" calibration at the maximum flow rate anticipated. A straight-line correlates the current reading and flow rate. An accuracy approaching the repeatability of 0.25% is possible by calibrating the flow meter for the anticipated flow rate range and correlating using a higher-order polynomial. Performing custom calibration of T-type thermocouples can reach an inlet water temperature accuracy of 0.1 K and fabricating a differential temperature transducer using two thermocouples and the bucking method can obtain an accuracy of 0.05 K [5].

8. Recommendations and Conclusions

In order to reach higher inlet temperatures, the supply and return plumbing should be insulated and auxiliary heaters implemented which can control and maintain the inlet temperature to within 0.1 K to conform to [3]. Artificial wind generators must be procured according to [3] to introduce the effect of wind. Current test installations and procedures conform to [2] and stricter conformance to installation and operating procedures of [3] should be applied to accurately obtain collector efficiency curves.

The facility is still in the validation phase with improvements noted in Section 7 underway to obtain the accuracy levels required. Requirements for [2] are exceeded when the required accuracy levels are reached, placing the STERG facility capabilities above that of the SABS facility. By implementing the recommendations above, conformance to performance testing of [3] can be achieved which will greatly help the commercial DSWH sector in Southern Africa. The facility is a remarkable improvement to previous solar energy testing abilities at the M&M Department. The addition in equipment is essential to further undergraduate and postgraduate studies at Stellenbosch University.

Acknowledgements

STERG wishes to thank the Austrian Development Agency for funding development of the facility and the Centre for Renewable and Sustainable Energy Studies at Stellenbosch University and AEE INTEC for facilitating the funds. The Stellenbosch University HOPE project is thanked for providing funds to complete the facility and present it at the SolarPACES 2011 conference. Gratitude is expressed to Rockwell Automation (Cape Town) for donating the PLC components and switchgear and Greenability (Cape Town) and SEG Solar Energy (Randburg) for donating the reference flat plate collector.

References

[1] W. Weiss, (2011), AEE INTEC, Personal communication.

[2] SANS 6211-1:2003, (2003), *Domestic Solar Water Heaters, Part 1: Thermal Performance Using an Outdoor Test Method*.

[3] DIN EN 12975-2:2006-06, (2006), *Thermal Solar Systems and Components – Solar Collectors – Part 2: Test Methods*.

[4] Solar collectors of the type FK 8231N 4H Cu-Al conforms to DIN EN 12975-1:2006-06, DIN EN 12975-2:2006-06 and Specific CEN KEYMARK Scheme Rules for Solar Thermal Products (Edition: 2003-01), (2008-06-03), Fraunhofer-Institute for Solar Energy Systems ISE.

[5] Prof. D.G. Kröger, (2011), Department of Mechanical and Mechatronic Engineering, Stellenbosch University, Personal communication.