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Lacour Ayompe
Technological University Dublin, lacour.ayompe@tudublin.ie

Aidan Duffy
Technological University Dublin, aidan.duffy@tudublin.ie

Sarah McCormack
Trinity College

See next page for additional authors

Authors

Lacour Ayompe, Aidan Duffy, Sarah McCormack, and Michael Conlon

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Validated TRNSYS model for forced circulation solar water heating systems with flat plate and heat pipe evacuated tube collectors

L.M. Ayompe [a,d,*], A. Duffy [a,d], S.J. McCormack [b], M. Conlon [c,d]

[a] Department of Civil and Structural Engineering, School of Civil and Building Services, Dublin Institute of Technology, Bolton Street, Dublin 1, Ireland
[b] Department of Civil, Structural and Environmental Engineering, Trinity College Dublin, Dublin 2, Ireland
[c] School of Electrical Engineering Systems, Dublin Institute of Technology, Kevin St, Dublin 8, Ireland
[d] Dublin Energy Lab, FOCAS Institute, Dublin Institute of Technology, Dublin 8, Ireland

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ABSTRACT

This paper presents a validated TRNSYS model for forced circulation solar water heating systems used in temperate climates. The systems consist of two flat plate collectors (FPC) and a heat pipe evacuated tube collector (ETC) as well as identical auxiliary components. The systems were fitted with an automated unit that controlled the immersion heaters and hot water demand profile to mimic hot water usage in a typical European domestic dwelling. The main component of the TRNSYS model was the Type 73 FPC or Type 538 ETC. A comparison of modelled and measured data resulted in percentage mean absolute errors for collector outlet temperature, heat collected by the collectors and heat delivered to the load of 16.9%, 14.1% and 6.9% for the FPC system and 18.4%, 16.8% and 7.6% for the ETC system respectively. The model underestimated the collector outlet fluid temperature by −9.6% and overestimated the heat collected and heat delivered to load by 7.6% and 6.9% for the FPC system. The model overestimated all three parameters by 13.7%, 12.4% and 7.6% for the ETC system.

1. Introduction

In developed countries, fuel consumption in the building sector accounts for 40% of the world's energy end use. Most of this consumption is used for heating, cooling, ventilation and sanitary hot water of which two-thirds is used in households where heating alone accounts for more than 50% [1]. Hot water is required for taking baths and for washing clothes, utensils and other domestic purposes in urban as well as in rural areas. Water is generally heated by burning non-commercial fuels, namely, firewood as in the rural areas and commercial fuels such as kerosene oil, liquid petroleum gas (LPG), coal and electricity (either by geysers or immersion heaters) in urban areas [2]. In this regard, utilization of solar energy through solar water heating (SWH) systems plays a big role in the quantity of conventional energy required [3]. Solar water heaters therefore have significant potential to reduce environmental pollution arising from the use of fossil fuels [4].

Solar water heaters are the most popular means of solar energy utilization because of technological feasibility and economic attraction compared with other kinds of solar energy utilization. Solar water heater technology has been well developed and can be easily implemented at low cost [5].

Almost all solar water heating systems used in temperate climates are active systems that make use of pumps to circulate the heat transfer fluid. These systems commonly use flat plate or evacuated tube collectors, which absorb both diffuse and direct solar radiation and function even under clouded skies. Water is heated in the collectors and a pump is used to circulate a water glycol mixture used as the heat transfer fluid. A solar controller triggers the pump when the difference between the temperature of water at the bottom of the tank and the heat transfer fluid at the outlet from the collector exceeds a set value. A solar coil at the bottom of the hot water tank is used to heat water. This fluid has some desirable properties such as low freezing and high boiling points. Their ease of operation and low cost makes them suitable for low temperature applications below 80 °C. An auxiliary heating system is used to raise the water temperature during periods when there is less heat available from the solar collector.

Temperate climates are those without temperature extremes and precipitation (rain and snow) with changes between summer and winter being generally refreshing without being frustratingly

* Corresponding author. Department of Civil and Structural Engineering, School of Civil and Building Services, Dublin Institute of Technology, Bolton Street, Dublin 1, Ireland.
E-mail address: lacour.ayompe@dit.ie (L.M. Ayompe).

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Fig. 1. Evacuated tube and flat plate collectors.

extreme. A temperate weather however, can have a very changeable weather in both summer and winter. One day it may be raining, the next it may be sunny. These climates are located in zones in the range of latitudes between 40 and 60/70°North.

Solar water heating collectors have been studied both experimentally and theoretically by a number of researchers. Azad [6] investigated the thermal behaviour of a gravity assisted heat pipe solar collector experimentally and theoretically using the effectiveness-NTU method. Hussein [7] developed and validated a simulation model for a wickless heat pipe flat plate solar collector with a cross flow heat exchanger. Riffat et al. [8] constructed a thin membrane flat plate heat pipe solar collector and developed an analytical model that was used to simulate heat transfer processes occurring in the collector and calculate its efficiency. Bong et al. [9] presented a validated theoretical model to determine the efficiency, heat removal factor, and outlet water temperature of a single collector and an array of flat plate heat pipe collectors. Ezekwe [10] analysed the thermal behaviour of solar energy systems using heat pipe absorbers and compared them with systems using conventional solar collectors. Bojić et al. [11] modelled and simulated the performance of a forced circulation solar water heating system using a time marching model.

Most of the studies carried out on solar water heating systems have been focused on solar collectors rather than the complete systems with very few studies reported in literature. However, several researchers have carried out studies on hybrid PV-thermal systems as reported in Kalogirou [12]. He modelled and simulated the performance of a hybrid PV-thermal solar system using TRNSYS and typical meteorological year (TMY) conditions for Nicosia, Cyprus.
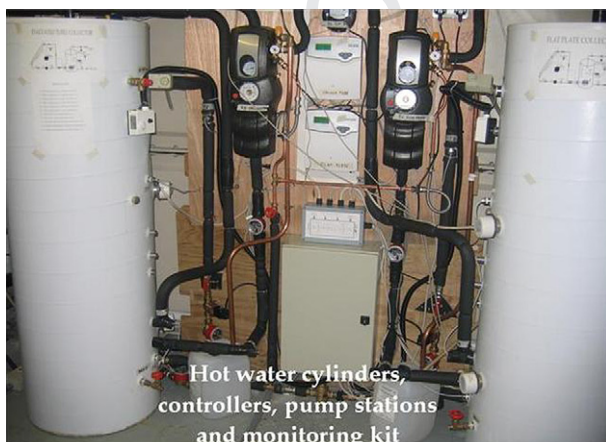

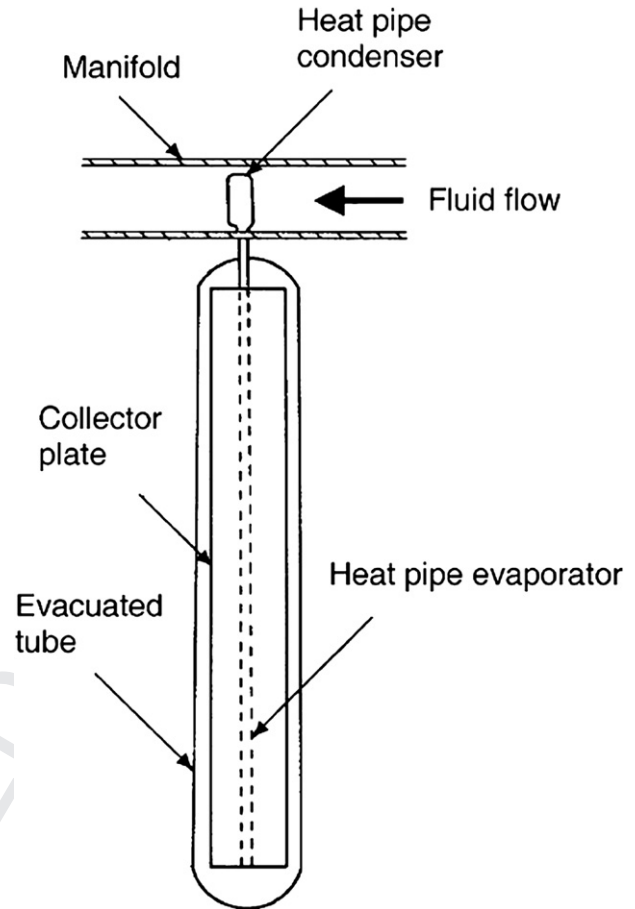**Fig. 2.** In-door installation of the experimental rig.

Fig. 3. Schematic diagram of a heat pipe evacuated tube collector.

The objective of this paper is to develop a TRNSYS simulation model for forced circulation solar water heating systems with flat plate and heat pipe evacuated tube collectors and validate the model using measured field performance data. The validated model will be useful for long-term performance simulation under different weather and operating conditions. The model could also be used for system optimisation under different load profiles.

2. System description

Typical solar water heating systems used in temperate climates consist of a hot water storage tank, control unit, pump station and either flat plate, evacuated tube or concentrating parabolic collectors. The collectors used in this study were installed on a flat roof of the Focas Institute building, Dublin Institute of Technology, Dublin, Ireland. They were south facing and inclined at 53° equal to the local latitude of the location. The hot water cylinders were installed nearby in the building's plant room. The solar circuits consisted of 12 mm diameter copper pipes insulated with 22 mm thick Class O Armaflex. All pipe fittings were also insulated to reduce heat losses. The solar circuit pipe lengths for the heat pipe evacuated tube collector supply and return were 14 m and 15.4 m respectively, while they were 14 m and 15.6 m respectively for the flat plate collector system. Figs. 1 and 2 show pictures of the evacuated tube and flat plate collectors as well as the in-door installations of the experimental rig.

The evacuated tube collector was a Thermomax HP200 consisting of a row of 30 heat pipe evacuated tubes and an insulated
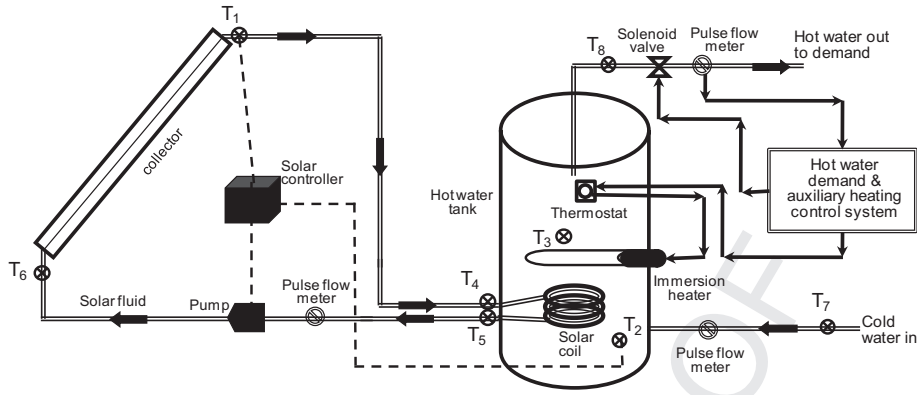
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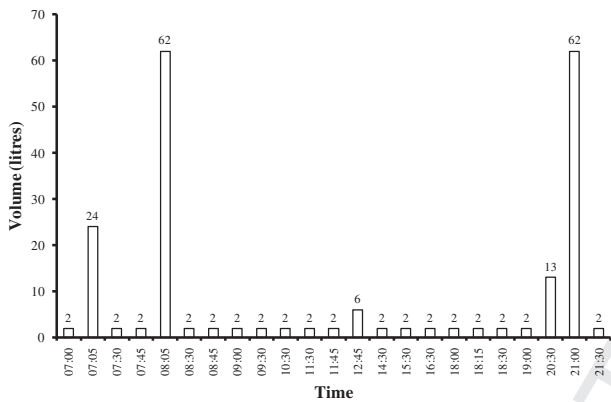**Fig. 4.** Schematic diagram of the solar water heating systems.

Fig. 5. Volume of hot water draw-off at different times of the day.

losses, so the collectors can operate at higher temperatures than FPC. Like FPC, they collect both direct and diffuse radiation. However, their efficiency is higher at low incidence angles. This effect tends to give ETC an advantage over FPC in day-long performance [13]. Heat pipes are structures of very high thermal conductance. They permit the transport of heat with a temperature drop, which are several orders of magnitude smaller than for any solid conductor of the same size. Heat pipes consist of a sealed container with a small amount of working fluid. The heat is transferred as latent heat energy by evaporating the working fluid in a heating zone and condensing the vapour in a cooling zone, the circulation is completed by return flow of the condensate to the heating zone through the capillary structure which lines the inner wall of the container [14,15].

The FPC system consisted of two K420-EM2L flat plate collectors each with a gross area of 2.18 m^2 and aperture area of 2 m^2 connected in series giving a total area of 4 m^2. Each collector had maximum operating and stagnation temperatures of 120 °C and 191 °C respectively, a maximum operating pressure of 10 bar and fluid content of 1.73 L.

Each system was equipped with a 300 L stainless steel hot water cylinder (model HM 300L D/coil U44332). The cylinder height and
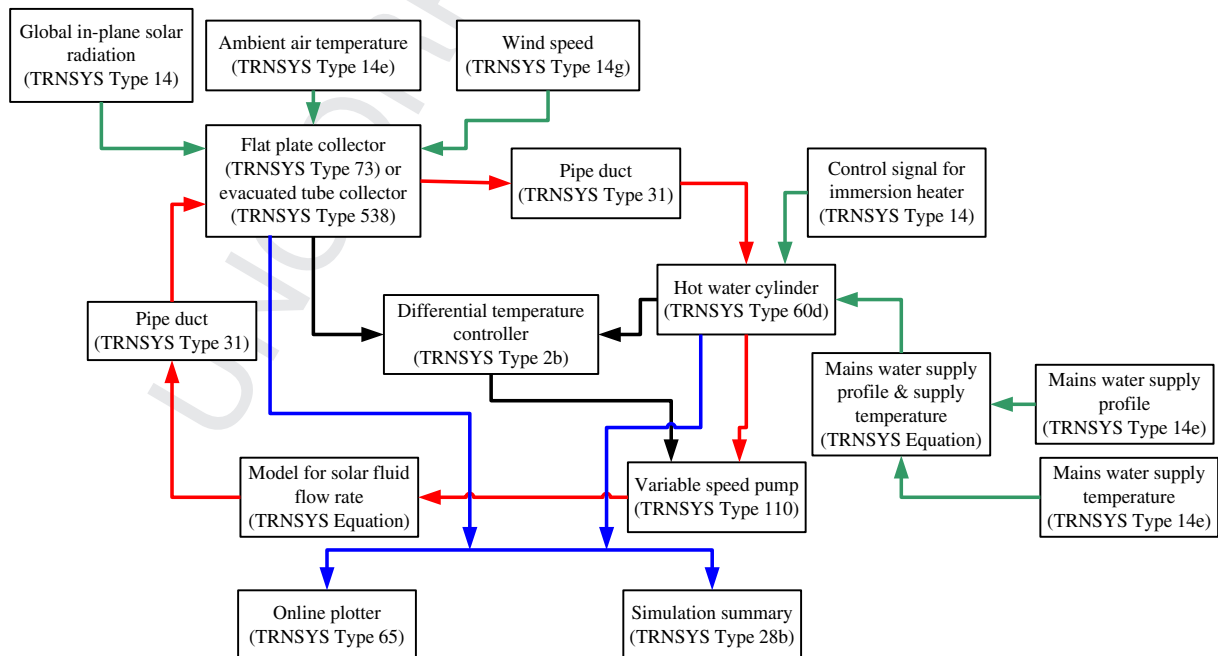
water manifold. The collector had an absorber surface of 3 m^2 and the tubes had a vacuum level of 10^{-5} mbar. These solar collectors consist of a heat pipe inside a vacuum-sealed tube, as shown in Fig. 3. The vacuum envelope reduces convection and conduction

Fig. 6. TRNSYS information flow diagram for the forced circulation solar water heating systems.

Table 1
Hot water cylinder parameters.

Parameter	Value	Unit
User specified inlet positions	2	
Tank volume	0.3	m^3
Tank height	1.68	m
Height of flow inlet 1	0.2	m
Height of flow outlet 1	1.6	m
Fluid specific heat	4.19	$kJkg^{-1} K^{-1}$
Fluid density	1000	kgm^{-3}
Tank loss coefficient	0.3	$Wm^{-2} K^{-1}$
Fluid thermal conductivity	1.4	$kJhr^{-1} m^{-1} K^{-1}$
Boiling temperature	100	°C
Height of 1st auxiliary heater	1	m
Height of 1st thermostat	1.5	m
Set point temperature for element 1	60	°C
Dead band for heating element 1	5	Delta C
Maximum heating rate of element 1	9900	$kJhr^{-1}$
Fraction of glycol	0.4	
Heat exchanger inside diameter	0.016	m
Heat exchanger outside diameter	0.02	m
Heat exchanger fin diameter	0.02	m
Total surface area of heat exchanger	1.4	m^2
Heat exchanger length	2.0	m
Heat exchanger wall conductivity	1.8	$kJhr^{-1} m^{-1} K^{-1}$
Heat exchanger material conductivity	1.8	$kJhr^{-1} m K^{-1}$
Height of heat exchanger inlet	0.4	m
Height of heat exchanger outlet	0.3	m

diameter were 1680 mm and 580 mm respectively, with an operating pressure of 3 bar. Each cylinder was fitted with two immersion heaters of 2.75/3.0 kW capacity located at the bottom and middle of the tank. The cylinders each had two heating coils with surface areas of 1.4 m^2 and 21 kW rating. The bottom coil was used by the solar heating circuit while the top coil was reserved for use with auxiliary heating systems such as boilers.

A programmable logic controller (PLC) turned on the immersion heaters between 5 and 8 am and 6–9 pm daily just before the two peak hot water draw-offs. Analogue thermostats placed at the top of the hot water cylinders were set to turn-off the electricity supply to the immersion heaters when the temperature of water at the top of the tank exceeded 60 °C. Fig. 4 shows a schematic diagram of the solar water heating systems.

Hot water was dispensed using solenoid valves that were opened and closed using signals from the PLC. Pulse flow metres (1 pulse per litre) installed at the end of the solenoid valves were used to count the number of litres of water extracted from the hot water cylinders. The solenoid valves were closed when the required volume of water was dispensed. The hot water demand profile employed was the EU reference tapping cycle number 3, featuring 24 draw-offs with the energy output of 11.7 kWh equivalent to

Table 2
Solar collector parameters.

Parameter	Unit	FPC (Value)	ETC (Value)
Number in series		2	1
Collector absorber area	m^2	3.95	3.021
Fluid specific heat	$kJkg^{-1} K$	3.708	3.708
Tested flow rate	$kghr^{-1} m^{-2}$		80
Intercept efficiency		0.776	0.778
First order efficiency coefficient	$kJhr^{-1} m^{-2} K^{-1}$	14.22	3.276
Second order efficiency coefficient	$kJhr^{-1} m^{-2} K^{-2}$	0.0594	0.036
Maximum flow rate	$Kghr^{-1}$	212	330
Collector slope	Degrees	53	53
Absorber plate emittance		0.7	
Absorbance of absorber plate		0.8	
Number of covers		1	
Index of refraction of cover		1.526	
Extinction coefficient thickness product		0.28	

Table 3
Pump parameters.

Parameter	Value	Unit
Rated flow rate (FPC)	212	$kghr^{-1}$
Rated flow rate (ETC)	330	$kghr^{-1}$
Fluid specific heat capacity	3.708	$kJkg^{-1} K^{-1}$
Rated power	226.8	$kJhr^{-1}$

a total volume of 200 L at 60 °C daily. It is based on the European Union mandate for the elaboration and adoption of measurement standards for household appliances EU M324EN [16]. Fig. 5 shows the recommended volume of hot water to be extracted at different times of the day.

3. Modelling

3.1. TRNSYS model

The solar water heating system model was developed using transient systems simulation (TRNSYS) software, which is a quasi-steady state simulation program. TRNSYS enables system components represented as proformas to be selected and interconnected in any desired manner to construct a system's model. In order to facilitate the selection of the system components, it is important to develop an information flow diagram. The information flow diagram for the models is shown in Fig. 6.

The main component of the model is the solar energy collector which is either a flat plate collector (Type 73) or evacuated tube collector (Type 538). Additional components to the model include: Type 31 pipe duct, Type 60d hot water cylinder with 1 inlet and 1 outlet, Type 2b differential temperature controller, Type 110 variable speed pump, Type 14 forcing functions, Type 65 online plotter and Type 28b simulation summary. Type 14 forcing functions were used several times in the model to input ambient air temperature and mains water supply temperature (Type 14e), wind speed (Type 14g), hot water demand profile (Type 14b), immersion heater control signals and in-plane solar radiation (Type 14h). Tables 1, 2 and 3 show values of parameters for the hot water cylinder, solar collectors and pump respectively used in the TRNSYS model.

3.2. Weather data

Weather for three days notably clear sky in summer (02/06/2009), intermittent cloud cover in autumn (25/11/2009) and heavily overcast in winter (20/01/2010) were chosen to represent different weather conditions prevalent in Ireland. These data were
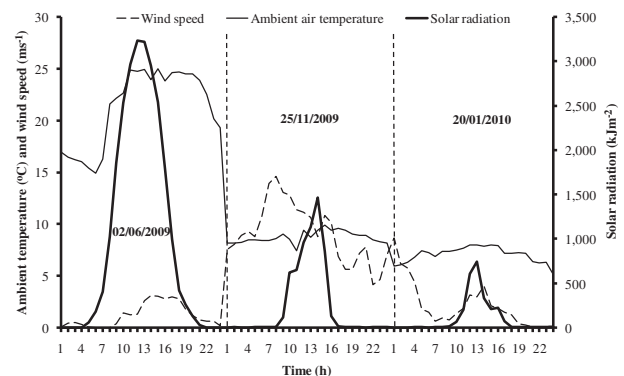

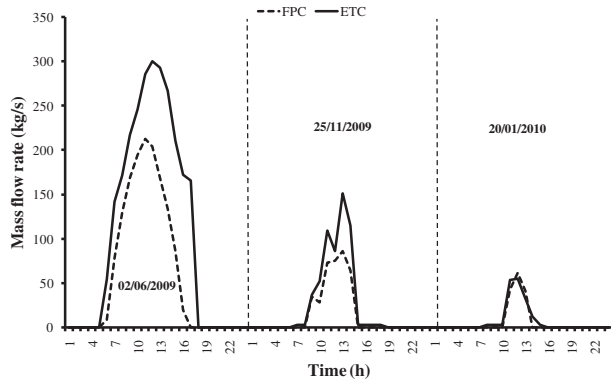**Fig. 7.** Solar radiation, wind speed and ambient air temperature.

Fig. 8. Solar fluid mass flow rate for the FPC and ETC systems.

used as inputs of the TRNSYS model. Fig. 7 shows plots of mean hourly values of solar radiation, ambient air temperature and wind speed. The maximum hourly values of in-plane solar radiation were 3234 kJm^{-2}, 1463 kJm^{-2} and 745 kJm^{-2} during the three days. The maximum hourly ambient air temperatures were 25.0 °C, 9.9 °C and 8.0 °C while the maximum wind speeds were 3.1 ms^{-1}, 14.6 ms^{-1} and 8.7 ms^{-1} respectively.

3.3. Mass flow rate

Fig. 5 shows plots of the measured solar fluid mass flow rate for the FPC and ETC systems. It is seen that the solar fluid mass flow rate was 212.4 kghr^{-1}, 85.8 kghr^{-1} and 61.5 kghr^{-1} for the FPC system and 300.2 kghr^{-1}, 151.5 kghr^{-1} and 54.9 kghr^{-1} for the ETC system during the clear sky, intermittent cloud covered and heavily overcast days respectively. For both systems the solar fluid mass flow rate shows clear dependence on the level of solar radiation.

The variable speed pump (TRNSYS Type 110) operates on an on/off sequence running at the maximum rate flow rates of 212 kghr^{-1} and 330 kghr^{-1} for the FPC and ETC systems respectively when on. This does not take into account the variable nature of the solar fluid mass flow rates shown in Fig. 8. The solar fluid mass flow rate was therefore modelled to reflect real-time operation of the actual pump. The fluid mass flow rate was seen to vary linearly with in-plane solar radiation and was modelled following the expression shown in Eq. (1).

$$\dot{m}_f = aG_t + b \tag{1}$$

where, a and b are empirical coefficients with values of 0.0623 and −2.1394 for the FPC system and 0.0976 and 2.059 for the ETC system determined using measured data. The correlation coefficients (R^2) for the FPC and ETC systems were 0.97 and 0.93 respectively. The solar fluid mass flow rate model in Eq. (1) was incorporated into the TRNSYS model using the equation proforma.

3.4. Heat collected

The useful energy collected by the solar energy collector is given as [17]:

Table 4
PMEA and PME for collector outlet temperature (T_{co}), heat collected by the collector (Q_{coll}) and heat delivered to the load (Q_{load}).

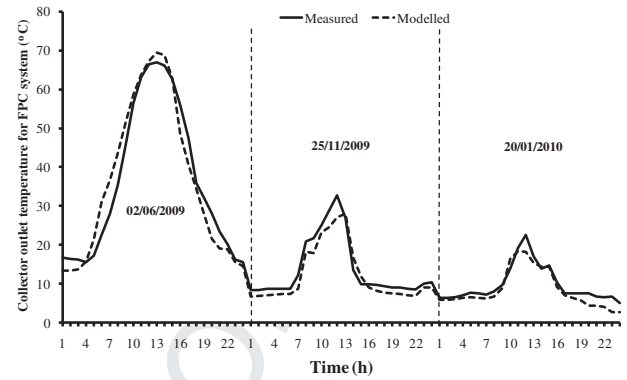|	PMAE			PME		
	T_{co}	Q_{coll}	Q_{load}	T_{co}	Q_{coll}	Q_{load}
FPC	16.9	14.1	6.9	−9.7	7.6	6.9
ETC	18.4	16.8	7.6	13.7	12.4	7.6

$$Q_{coll} = \dot{m}_f C_{pf}(T_1 - T_6) \tag{2}$$

3.5. Heat delivered

The heat delivered by the solar water heating system to the load was calculated as

$$Q_{load} = \dot{m}_w C_{pw} T_{8,avg} \tag{3}$$

3.6. Hot water demand

Since the hot water tanks used in this study are pressurised, the hot water demand profile shown in Fig. 5 was modelled using two TRNSYS Type 14e forcing functions each representing the mains water supply profile and temperature respectively. The outputs from the forcing functions were then combined using a TRNSYS equation proforma that had as output the mains water supply profile and temperature.

3.7. Model validation

In order to quantify variations between predicted and measured values, percentage mean absolute error (PMAE) and percentage mean error (PME) were used. PMAE evaluates the percentage mean of the sum of absolute deviations arising due to both over-estimation and under-estimation of individual observations. The PME evaluates the percentage mean of the sum of errors of individual observations. A negative value of PME indicates a net underestimation while a positive value indicates a net overestimation of the modelled values. PMAE and PME are given in Eqs. 4 and 5 as:
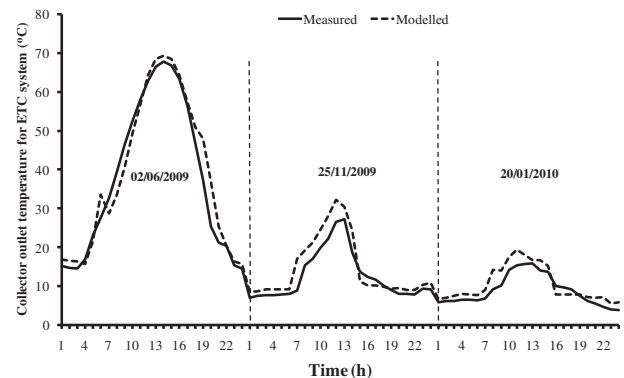

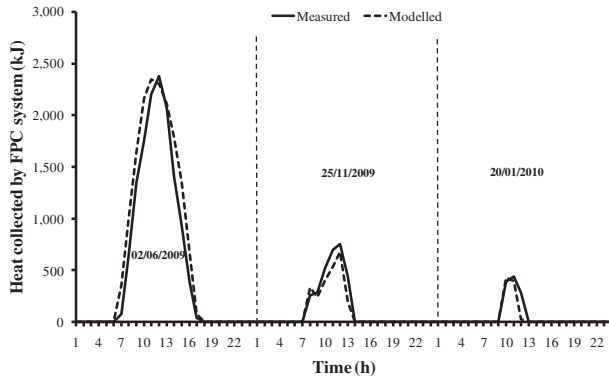**Fig. 9.** Measured and modelled collector outlet temperature for FPC system.

Fig. 10. Measured and modelled collector outlet temperature for ETC system.

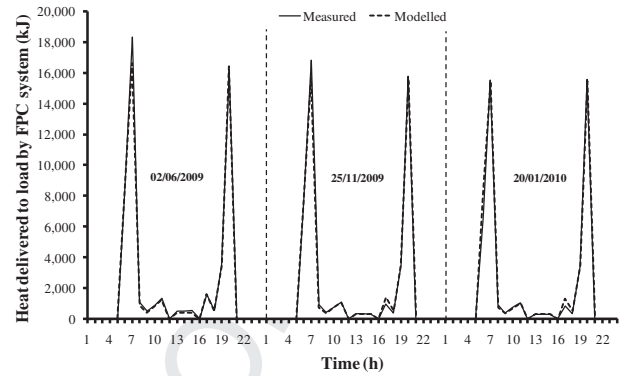Fig. 11. Measured and predicted heat collected by the FPC system.

$$PMAE = \frac{100}{N} \sum_{i=1}^{N} \frac{|C_i - M_i|}{M_i} \qquad (4)$$

and

$$PME = \frac{100}{N} \sum_{i=1}^{N} \frac{C_i - M_i}{M_i} \qquad (5)$$

N is the total number of observations while C_i and M_i are the ith calculated and measured values, respectively.

4. Results and discussions

Table 4 presents percentage mean absolute errors (PMAE) and percentage mean error (PME) for collector outlet temperature (T_{co}), heat collected by the collector (Q_{coll}) and heat delivered to the load (Q_{load}) for both the FPC and ETC systems. The results show that the model performed slightly better in all six cases for the FPC system. It however, predicted Q_{load} for the FPC system with the least PMAE of 6.9% while it predicted T_{co} for the ETC system with the highest PMAE of 18.4%. The negative value of PME for the FPC indicates an underestimation of T_{co} by the model.

Much of the discrepancies between the simulated and experimental results can be attributed to experimental errors which are a function of the accuracy of the measurement devices used. Also, the existing TRNSYS proformas for evacuated tube collectors might not be fully representative of heat pipes. Detailed plots of the results are presented in Sections 4.1–4.3.
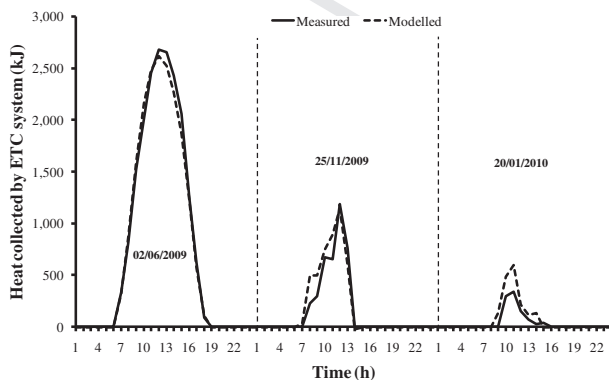

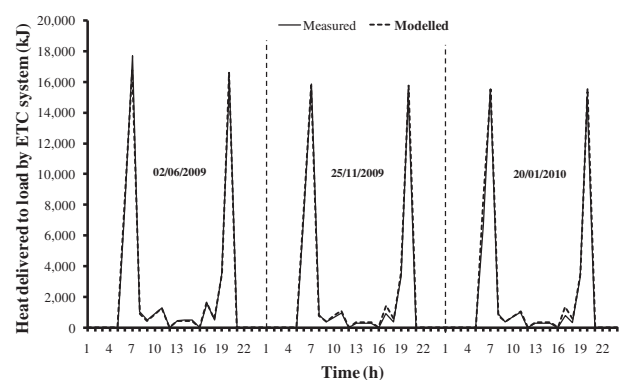Fig. 12. Measured and modelled heat collected by the ETC system.

Fig. 13. Measured and modelled heat delivered to load by FPC system.

4.1. Collector outlet temperature

Fig. 9 shows plots of measured and modelled collector outlet temperature (T_{co}) for the FPC system. It is seen that the modelled values follow the same trend as the measured values. The model however overestimated T_{co} during the bright sunny day (02/06/2009) while it underestimated same during the other two days. Fig. 10 shows plots of measured and modelled values of T_{co} for the ETC system. Again it is seen that the modelled values follow the same trend as the measured values. The model however, overestimated T_{co} during all three days.

4.2. Heat collected

Fig. 11 shows plots of measured and modelled heat collected (Q_{coll}) by the FPC. It is seen that the modelled values follow the same pattern as the measured values. The model slightly overestimated Q_{coll} on the bright sunny day (02/06/2009) and underestimated Q_{coll} during the other two days. Fig. 12 shows plots of measured and modelled heat collected (Q_{coll}) by the ETC. It is seen that the modelled values follow the same pattern as the measured values. The model slightly underestimated Q_{coll} on the bright sunny day (02/06/2009) and overestimated Q_{coll} during the other two days.

The high discrepancy between the modelled and measured Q_{coll} for the ETC system was as a result of the nature of operation of the heat pipe evacuated collector which has two different circuits. The evaporation and condensation cycle of the primary heat transfer fluid in the primary circuit as well as heat removal through the secondary circuit causes the pump to intermittently switch on and off in quick succession. This sometimes results in energy loss from the hot water tank thereby reducing the net energy collected.

Fig. 14. Measured and modelled heat delivered to load by ETC system.

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4.3. Heat delivered to load

Figs. 13 and 14 show plots of measured and modelled heat delivered to the load for the FPC and ETC systems. It is seen that the model predictions for both the FPC and ETC systems closely followed the same trend as the measured heat delivered to the load during the three days with the model slightly overestimating the quantity of heat delivered to the load.

5. Conclusions

A TRNSYS model was developed for forced circulation solar water heating systems with flat plate and heat pipe evacuated tube collectors. The model was validated using field trial data for systems installed in Dublin, Ireland. Results obtained showed that the model predicted the collector outlet fluid temperature with percentage mean absolute error (PMAE) of 16.9% and 18.4% for the FPC and ETC systems respectively. Heat collected and delivered to the load was also predicted with PMAE of 14.1% and 6.9% for the FPC system and 16.9% and 7.6% for the ETC system respectively. The model underestimated the collector outlet fluid temperature by −9.6% and overestimated the heat collected and heat delivered to load by 7.6% and 6.9% for the FPC system. The model overestimated all three parameters by 13.7%, 12.4% and 7.6% for the ETC system.

The validated TRNSYS model can be used to:

- Predict long-term performance of the solar water heating systems in different locations
- Simulate system performances under different weather and operating conditions
- Optimise solar water heating system sizes to match different load profiles.

Nomenclature

C_{pf}	specific heat capacity of solar fluid (kJkg^{-1} K^{-1})
C_{pw}	specific heat capacity of water (kJkg^{-1} K^{-1})
ETC	evacuated tube collector
FPC	flat plate collector
G_t	in-plane solar radiation (kJm^{-2})
$\dot{m}_f$	solar fluid mass flow rate (kghr^{-1})
$\dot{m}_w$	water mass flow rate (kghr^{-1})
PMAE	percentage mean absolute error (%)
PME	percentage mean error (%)
Q_{coll}	heat collected by solar collector (kJ)
Q_{load}	heat delivered to load (kJ)
T_1	solar fluid temperature at collector outlet (K)
T_6	solar fluid temperature at collector inlet (K)
$T_{8,avg}$	average hot water temperature delivered to load (K)
TRNSYS	transient systems simulation
SWH	solar water heating

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