# Simulation of a novel combined water purification and electricity generation system

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## Abstract

This paper presents a selection of results from a one-dimensional simulation of an indirect solar thermal steam generator coupled to a steam expansion engine. The model was developed in Flownex SE and allows for prediction of the system performance as a function of transient solar and ambient conditions. Results from a sunny summer and overcast winter day are presented. The pilot system is able to produce 74 L of water and 1.2 kWh mechanical power at a SEC of 650 kWh/m<sup>3</sup>. Validation of the results against experimental measurements is pending.

Keywords: Solar thermal energy, solar distillation, desalination, steam expansion, heat engine

# 1. Introduction

## 1.1. Background

There is a global push for countries to become more environmentally friendly and this push led the United Nations (UN) to adopt the Sustainable Development Goals (SDGs) in 2015. The SDGs provide a framework of goals and targets to move "toward a global sustainable future" (Keitsch, 2018). This led to an increase into research of renewable and sustainable energy systems.

Due to the abundance of low to medium temperature energy sources (100 to 150 °C), such as biomass, geothermal, industrial processes and non-concentrating solar thermal; there is a renewed interest in devices which can harness this energy (Bortolin et al., 2021). The Organic Rankine Cycle (ORC), which employs working fluids with evaporation temperatures below 100 °C, is the most advanced technology for harnessing low-grade thermal energy. However, ORC systems are complex, operate at high pressures and are economical only for power outputs greater than 100 kW (Müller & Howell, 2021). The University of Southampton has been conducting research into using steam engines as an alternative (and possibly cheaper) means of harnessing low-grade thermal energy at low pressure (~1 atm) (Müller et al., 2017; Müller & Howell, 2021).

There is a collaboration between the University of Southampton and Stellenbosch University (SU), for the development of solarized steam engine for combined water purification / desalination and energy generation at small scale. The experimental system, Figure 1, consists of an indirect solar thermal steam generator connected to an expansion engine. Steam is produced at approximately 1.1 bar using solar thermal energy. The steam then undergoes adiabatic expansion in the engine to produce work before being condensed. The condensate is collected for human use.



Figure 1: Experimental system layout

## 1.2. Objectives

The aim of this project is to develop a validated process model in Flownex SE for the proposed system to (a) identify important parameters for optimisation in the design and operation of the experimental system, and (b) calculate the annual production of distilled water and electricity potential to determine technical feasibility. The model can be used for parametric analysis beyond the scale of the current system which can help with determining the overall feasibility of the concept. This paper will present the model and results for a summer and winter's day.

## 2. System description

The steam expansion engine developed by the University of Southampton for this project has a design maximum steam mass flow rate  $(\dot{m}_{st})$  of 2.56 g/s. Using Equation (1, the required rate of energy input  $(\dot{Q}_{req})$  is determined to be 5.78 kW for a boiler pressure of 1 atm.

$$\dot{Q}_{reg} = h_{fg} \, \dot{m}_{st} \tag{1}$$

The solar thermal collector loop was sized to provide the 5.78 kW of input thermal power for a Direct Normal Irradiance (DNI) of  $850 \text{ W/m}^2$ , as this DNI is used in the ISO 9806:2017 standard for solar thermal collector performance reporting (European Committee for Standardization, 2017). An indirect solar loop was selected to avoid excessive fouling in the collector loop if saline / dirty water were used directly (Ferry et al., 2020). An external compound parabolic concentrator (XCPC) collector was selected as this has greater efficiency at higher temperatures compared to evacuated tube collectors and flat plate collectors (Widyolar et al., 2021). The system uses six Artic Solar Emperor LH-3-2M XCPCs to provide the required input heat, Figure 2. The collectors are connected in three parallel branches with two collectors in series in each branch.



Figure 2: Artic Solar XCPC (Artic Solar, 2021)

An eighty-litre boiler with an internal heating coil of  $0.7 \text{ m}^2$  and a 6 kW electric heating element was manufactured specifically for the system.

The heat transfer from the fluid in the coil to the water in the boiler causes the water to boil and form steam. The steam is then drawn from the boiler to the expansion engine whereby it undergoes adiabatic expansion (Müller & Parker, 2015; Müller et al., 2017; Müller & Howell, 2021). During expansion, the engine's piston is pushed down, which causes a crank shaft to turn and produce mechanical power which can be converted to electricity if desired. A condenser is coupled to the outlet of the expansion engine to condense the steam and maintain a vacuum which facilitates the necessary pressure difference across the engine. The condensate at the outlet of the condenser is collected.

A basic control system is implemented to control the feedwater supply (triggered by a boiler water level switch) and the opening and closing of inlet and outlet valves for the boiler and engine. A boiler outlet valve is opened when the boiler pressure reaches 1.12 bar to prevent pressurization in the boiler. The engine inlet and outlet valves (see Figure 5) are controlled using a position sensor on the crank.

# 3. Research methodology

A one-dimensional process model of the experimental system was developed in Flownex, a dedicated thermofluid network solver software. Flownex solves the fundamental governing equations of mass, momentum and energy using the Implicit Pressure Correction Method (Flownex SE, 2021).

Flownex has built in components such as: pipes, heat exchangers, valves, pumps and heat transfer components. This allows for standard items such as control valves and circulating pumps to be dragged into a user interface (referred to as a "drawing canvas") and provided with user defined physical dimensions and performance curves. Flownex also allows for custom components to be incorporated via user defined scripts.

Figure 3 shows the Flownex model of the experimental system. The boundary conditions (Table 1) are set to pressure, mass flow rate or temperature at the beginning and end of each stream. Pipe elements connect the components to accurately simulate the pressure drop during transient operation. A description of the primary component models follows.



Figure 3: Flownex model

## Table 1: Table of boundary conditions

Component	Value
Water supply tank temperature and pressure at free surface	25 °C & 1 atm
Condenser outlet pressure (maintained by a vacuum pump)	7.38 kPa
Solar loop HTF mass flowrate (pump driven)	0.054 kg/s
Condenser cooling water temperature and flow rate	20 °C & 0.167 kg/s

# 3.1. Solar collector network

The useful thermal power in each collector is a function of the solar resource and collector efficiency as shown in equation (2. The collector efficiency is determined using the method prescribed by Ferry et al. (2020). The solar resource is quantified in terms of Global Tilt Irradiance (GTI), calculated using the method prescribed by Widyolar et al. (2021) for the XCPC. Useful thermal power results in an increase in the HTF temperature as it flows through the collector and collectors in series receive heated inlet water from the outlet of the upstream collector. Hot HTF at the collector outlet is piped to the boiler to heat water and generate steam.

$$\dot{Q}_{\mu} = \eta A_{col} GTI_{cpc} \approx \dot{m} c_p A_{col} (T_o - T_i)$$
<sup>(2)</sup>

## 3.2. Boiler

The boiler could not be modelled using a standard Flownex heat exchanger component since it involves both sensible heating and boiling and thus multiple heat transfer coefficients. The boiler was thus manually modelled using a two-phase tank, composite heat transfer and pipe elements; as can be seen in Figure 3.

A composite heat transfer (CHT) element was used to incorporate heat loss to the environment. A pipe element was used to represent the submerged helical coil carrying the solar loop heat transfer fluid (HTF) on the inside. The heat transfer between the HTF and the pool water was modelled using a CHT element as well. The CHT element calculates the heat transfer rate considering tube side convection, conduction through the pipe wall and the shell side convection.

The internal convection heat transfer coefficient (HTC) is based on the well-known Dittus-Boelter correlation with modified coefficients specific to helical coils presented by Xin & Ebadian (1997), equation (3.

$$Nu = 0.0062 \, Re^{0.92} \, Pr^{0.4} \left( 1 + 3.455 \frac{D_{tube}}{D_{coil}} \right) \tag{3}$$

The shell side HTC is dependent on the tube wall, pool and saturation temperatures. Figure 4 shows the algorithm employed for calculating the shell side HTC.



Figure 4: Shell side HTC algorithm

The experimental HTC correlation for natural convection in a hot water storage tank heated by submerged coils developed by Fernández-Seara *et al.* (2007) is used for both sensible heating by natural convection and convective boiling (Bejan, 2013), the correlation can be seen in equation (4.

$$Nu_{do} = 0.4998 \, Ra_{do}^{0.2633} \tag{4}$$

Equation (5 is the widely used correlation for nucleate boiling developed by Rohsenow (1951) as reported by Masterson (2020).

$$h_{nb} = \mu_l h_{fg} \sqrt{\frac{g(\rho_l - \rho_v)}{\sigma} \left(\frac{c_{pl}}{C_{sf} h_{fg} P r_l^n}\right)^3} (\Delta T_e)^2$$
(5)

Due to the unknown nature of transition and film boiling, when the excess temperature  $(\Delta T_e = T_{wall} - T_{sat})$  exceeds 30 °C, the script uses the critical heat flux equation presented in Cengel & Ghajar (2015), the correlation can be seen in equation (6.

$$\dot{q}_{max} = 0.12 \, h_{fg} \sqrt{\rho_v} [\sigma g \, (\rho_l - \rho_v)]^{1/4} \tag{0}$$

 $\langle \alpha \rangle$ 

#### 3.3. Expansion engine

The expansion engine developed by the University of Southampton is a modern version of James Watt's steam engine of 1776. The original Watt engine was able to achieve a thermal efficiency of 3.5 % (Müller & Parker, 2015). The experimental engine has a theoretical efficiency of 6.3 %, for steam input temperature of 100 °C and condenser temperature of 40 °C (Müller & Howell, 2021). Figure 5 illustrates the workings of the engine.



Figure 5: The steam expansion engine cycle

Müller et al. (2017) provides the theory on the work produced during the steam expansion. The expansion engine script uses this theory to determine the outlet steam enthalpy and mechanical power production.

Equation (7 is used to calculate the theoretical maximum work produced by the engine during the expansion cycle, with  $\gamma = 1.08$  for wet steam.

$$W_{tot} = A_p \left( p_0 \cdot L_0 + \frac{1}{\gamma - 1} (p_0 \cdot L_0 - p_1 \cdot L_1) - p_{cond} \cdot L_1 \right)$$
(7)

Equation 7 does not include the steam flow rate and thus cannot be used for calculating the real engine work under variable operating conditions. For this reason, the isentropic work equation (equation (8) is used to determine the work conducted by the steam during expansion.

$$W_{real} = \dot{m}_{st} \left( h_1 - \eta (h_1 - h_{cond, isentropic}) \right)$$
(8)

where,  $h_1$  is determined from steam tables using the engine inlet steam pressure and quality and  $h_{cond,isentropic}$  is determined from steam tables using the condenser pressure and inlet entropy. An isentropic efficiency ( $\eta$ ) of 15%, results in  $W_{real} = W_{tot}$  at the design mass flowrate and was used as a constant value in Equation 8.

# 3.4. Condenser

The condenser is connected to the outlet of the expansion engine. The condenser is a double pipe counter flow heat exchanger. The inner pipe contains the cooling water and the steam flows through the annulus region. The condenser is modelled in Flownex using the standard heat exchanger component, which has built-in correlations for steam condensation. The outlet of the condenser is maintained at a constant pressure due to a connected vacuum pump.

# 4. Results

The Southern Africa Radiometric Network (SAURAN) provides historical solar data for locations around Southern Africa. Solar Direct Normal Irradiance (DNI), Diffuse Horizontal Irradiance (DHI) and ambient temperature data was downloaded for the year 2020, with a one-hour time averaged interval from SAURAN, at the Stellenbosch University monitoring station.

1 January 2020 and 26 June 2020 were chosen as case studies for this paper as they represent a sunny summers day and an overcast winters day, respectively. The daily solar irradiation recorded was respectively  $5.6 \text{ kWh/m}^2/\text{day}$  and  $1.9 \text{ kWh/m}^2/\text{day}$ .

Results are shown from 9am to 5pm with the water preheated to show the stored heat from the previous day.

## 4.1. Engine mechanical power

For boiler and condenser pressures of 110 kPa and 7.4 kPa, expansion engine physical dimensions and equation (7, the theoretical maximum mechanical power is determined to be 223 W. Figures 6 and 7 show the mechanical power produced alongside the heat input to the boiler. The mechanical power is related to the steam mass flowrate, and this explains the periodic drops in mechanical power as the steam flow is interrupted during refilling of the boiler.

By integrating both the output power and heat transfer curves, the engine can theoretically produce 1.2 kWh of mechanical energy on the summer's day (when supplied with 24.4 kWh of thermal energy in the boiler) and 0.36 kWh on the winter's day (input thermal energy of 14.5 kWh).



Figure 6: Engine power and coil to boiler heat transfer for 1 January 2020



Figure 7: Engine power and coil to boiler heat transfer for 26 June 2020

## 4.2. Distillate production

Figure 8 shows the produced steam mass flow rate (and thus distillate production) and GTI for 1 January 2020. The model predicts that the experimental system will produce 74 L of distillate for on this summer's day. The sudden drops in mass flow rate are due to cold water being pumped into the boiler to replenish the water level. As Flownex models the two-phase tank as single node, the addition of cold water results in Flownex predicting guenching and total pressure drop (De Klerk, 2020) which results in the boiler outlet valve closing until sufficient pressure is built up again.





The specific energy consumption (SEC) for the distillate for 1 January 2020 is  $650 \text{ kWh/m}^3$ based on coil thermal energy input. For 1 January 2020, the collector network received 90.7 kWh of GTI and thus the overall SEC of the experimental system is 1219 kWh/m<sup>3</sup>. Figure 9 shows the distillate mass flowrate and GTI for 26 June 2020.

The experimental system is predicted to produce 22 L of distillate on this day at a coil heat SEC of  $649 \text{ kWh/m}^3$ , and an overall solar-to-distillate SEC of  $1423 \text{ kWh/m}^3$ .



## 5. Conclusions and recommendations

This paper presents a model of an experimental solar thermal powered water purification/desalination and electricity production system. The model is used to predict the output of the system on a sunny summer day and overcast winter day. Validation of the model against experimental data is pending.

For a daily GTI of  $5.6 \text{ kWh/m}^2$ , the experimental system will produce 74 L of distillate and 1.2 kWh of mechanical energy with a SEC of  $650 \text{ kWh/m}^3$  for coil input energy. When compared to other means of desalination, such as, solar powered reverse osmosis with SEC of  $4 \text{ kWh/m}^3$  and multiple effect distillation (MED) with SEC of  $50 \text{ kWh/m}^3$ , the proposed system proves to be inefficient. Regardless, the system has the potential to provide distilled water even on days with low solar resources and the combination of water purification and energy production is attractive. The effect of system scale, parametric configuration (including operational set points) and cost of product compared to alternative systems (and ORCs in particular) remains to be investigated.

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