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Modelling and Optimization of Small Scale Solar Organic Rankine Cycle for Islamabad, Pakistan

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***Abstract*—**In recent decades, energy demand has grown exponentially. Fossil fuels, which today meet the bulk of global energy demand, can be gradually replaced by renewable energies, thus limiting its dangerous consequences such as climate change, environmental pollution, depletion of natural resources, etc. Solar energy can play an important role in the satisfaction of energy demand, especially in a heavily sun-ridden country. The current study focuses on the modelling and optimization of Organic Rankine Cycle (ORC) based on different organic fluids operating in a temperature range below 50-100 °C. The ORCs are a good choice to produce small-scale energy due to the lower temperature range of 50 to 99 °C. They are therefore simple and inexpensive. Flat plate (FPC) or evacuated tube solar collectors (ETC) can also provide the desired energy. In this work, two system configurations are analyzed. In configuration-I (C-I), the water from the collector outlet moves to the hot water storage tank (HWST) connected in series, while in configuration-II (C-II), HWST is not used. Therefore, the hot water from the solar collector outlet enters directly into the auxiliary heater (which will be lit if necessary, otherwise) and the water return from the heat exchanger will become the input of the solar collector. Working fluids suitable for a solar-powered ORC at a temperature of 100 °C or lower are selected using predefined criteria such as higher fluid densities, maximum cycle efficiency, safety and environmental data, a moderate temperature and inexpensive and uncomplicated equipment. The R125 and R245ca were found to be good fluids due to the minimum collector area for the desired yield and maximum efficiency, respectively. For the R125, the minimum required collector area is estimated to be 50 m² for the ETC and 68.14 m² for the FPC. For these areas, the optimized size of the HWST is estimated at 1350 L. System configurations are modelled and simulated in TRNSYS for the entire year, from January 1st to December 31st, to investigate optimal collector tilt, the smallest collector area for maximum solar fraction, and solar collector thermal efficiency. Monthly solar collector efficiency is calculated for both configurations. The results of the simulation showed that C-II gives a comparatively higher solar collector thermal efficiency and solar fraction. For both collectors, the maximum seasonal solar fraction is obtained at an inclination of approximately 14°. A thermal efficiency of evacuated tube solar collector is comparatively higher for C-II than that of C-I and one observes the same trend for FPC. In addition, the thermal efficiency of the ETC at 50 m² is higher than that of the FPC at an area of 68.14 m².exhibited.

***Keywords*—** Organic rankine cycle, Trnsys, flat plate collector; evacuated tube collector, solar fraction, tilt angle.

I. Introduction

FOSSIL fuels fulfilled the energy demand throughout the entire modern era. Coal, oil and natural gas remained in use for ages. However, accelerated human development threatened the sustainability of these energy sources. The persistent and widespread reliance on fossil fuel resources so far led to their depletion. It also challenged environment by an increase in air pollution and global warming. This caused a search for renewable sources of energy that ensure a sustainable future for the humanity. For production and industrial processes global economy revolves around energy. The efficient energy production and its use have a significant consequence on our society and environment as well. As per International Energy Agency (IEA), the current trend for energy consumption and efficiency increases energy requirement by 70% and 60% and emissions respectively by 2050 in comparison to 2011. The global average temperature by associated emissions will increase by 6 °C by 2050, which might result in massive adverse impact i.e. climate change, energy security and unendurable future [1].

The fossil fuel burning generates nearly 21300 million tons of toxic carbon dioxide (CO2) every year. As per reports it is claimed that natural processes absorb only about half of this amount thus there is net increase of 1065 million tons of atmospheric CO2 every year. [2] Renewable energy sources are an alternative to conventional fossil fuels which are available in various forms and their energy can be harnessed through various means. There is no region in the world that lacks one form of renewable energy source or another but their abundance might vary. Getting energy from renewable sources like solar, wind, hydro, biomass, geothermal and industrial waste heat is becoming attractive to conventional sources. Research into efficient, effective and energy harnessing techniques from renewable sources is trending worldwide. In 2016, clean energy installations of 160 GW introduced globally. This shows an increase of 10% compared to 2015, but their cost is reduced almost a quarter. Furthermore, solar power provided the biggest boost and consisted of half of all new capacity. 2016 was the first year in history that introduced solar capacity that surpassed all other electricity-producing technologies. [3].

Many techniques generate electricity from low temperature thermal energy for the reduction of environmental pollutants and ORC is amongst them. The Rankine cycle technology, one of the incipient energy conversion techniques, harnesses energy from renewable sources efficiently and effectively. Compression of wet vapors in Carnot cycle became a problem so ORCs stepped in as an advancement. Rankine cycle comprises four main thermodynamic processes namely compression, evaporation, expansion and condensation. Four main components of the cycle namely the pump, boiler/ evaporator, turbine/expander, and condenser perform these processes. The technology of ORCs is applicable in various applications such as geothermal, hydropower, wind, solar, biomass and industrial waste heat recovery etc. High, medium and low-grade heat sources are defined by their temperature facilitate such applications. Medium to high thermal sources provide high efficiency of an ideal Rankine Cycle (RC) system with temperatures above 370 °C. The ORC operates on the same principle as that of an ideal RC with the exception of using organic fluid as working fluid. The effective utilization of low-grade energy resources gives ORC a great advantage. The additional features of the organic Rankine technology such as dry expansion process, low adverse environmental impact, high thermal efficiency, simple expander design make it a valuable technology. For many years, the research trend shifted towards power generation from sustainable and clean resources. Industrialization, socio-economic and environmental factors mainly contribute to this trend.

Small-scale Solar Organic Rankine cycles are best suitable for off-grid remote areas. In comparison to the PV collectors, solar ORCs usually have local manufacturing. They also show much more flexibility that allows the hot water production as a byproduct for domestic or industrial use with a low appropriate investment cost. For medium and large scale, the technology is much developed but only a few solutions are available for small size systems in the low kW power range. The evolution of small organic Rankine power systems is due to lack of efficient components for decades.

Pakistan faced severe energy crisis since the last two decades. The region shows sufficient solar radiation but lacks solar assisted ORC on small scale. This opens a doorway to research that determines the potential of solar energy to fulfil energy demand in remote areas on domestic level in Pakistan. Results from this research work address some of the fundamental issues linked with the conventional way of energy generation from fossil fuel, moreover, present the benefits of renewable energy production. This research aims to:

- Conduct a comprehensive literature review of the renewable energy resources and the technologies being used to capture them.
- Develop and optimize a suitable model for ORC that works in low temperature range.
- Present the output of ORC system in terms of generated power and efficiency.
- Show the effects of variation in input parameters i.e. pressure, heat source temperature and refrigerant flow rates, for the model developed and on the solar ORC performance thus determining optimum performance conditions.

The current research presents the power production potential available in renewable energy sources with low to medium temperature range. Factors which influence the selection of working fluid for the ORC technology are discussed in detail and selection of appropriate refrigerants is made. In the standard formulation of this research work, the law of conservation of energy has been carefully examined.

The cost analysis and evaluation of the materials used for the current study were not taken into account.

A. Algorithm

The algorithm for the modelling and optimization of small scale solar Organic Rankine Cycle is given in figure 1.

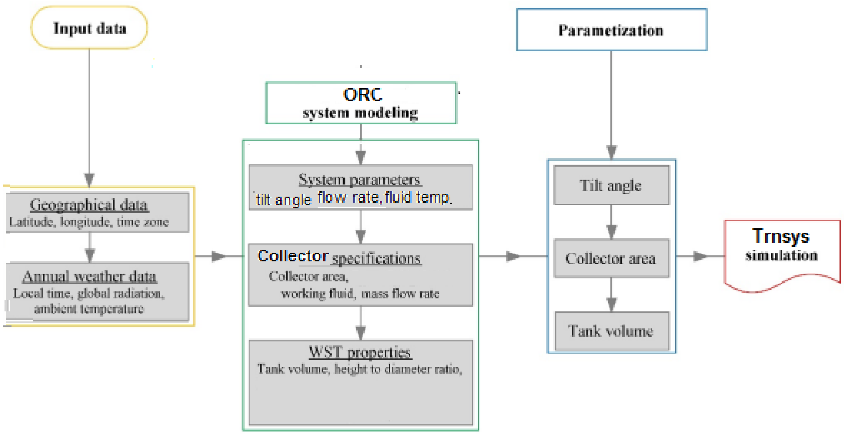

Figure 1: Algorithm for Modelling and Optimization in Trnsy

II. METHODOLOGY

The system consists of two circuits: the primary and the secondary circuit. The working fluid expands in the turbine in the primary circuit from where it goes into a condenser where it is condensed. In the secondary circuit, the pump circulates the hot water of the solar collector (Type 1b or 71) in the hot water tank (Type 4a). And two possibilities are discussed: solar collectors without solar thermal energy storage tank (CI) and solar collectors connected to a solar thermal energy storage tank (C-II). Solar collector thermal efficiency is calculated by:

$$\eta = a_0 - a_1 \frac{\Delta T}{I_T} - a_2 \frac{\Delta T^2}{I_T} \quad (1)$$

where:

$\Delta = (Tin - Tamb)$

In this study values of ao, a1 (W/m².K) and a2 (W/m².K²) are taken as 0.845, 1.47 and 0.01 for ETC and 0.749, 2.770 and 0.023 for FPC, respectively. These values are taken from a manufacturer "Apricus" collector's catalogue. a0, a1 and a2 define the thermal efficiency. [4] The equations 1 and 2 calculate the capacity of each side of the heat exchanger [5].

$$C_c = m_c C_{pc} \quad (2)$$

$$C_h = m_h C_{ph} \quad (3)$$

Equation (4) is used to calculate the heat exchanger effectiveness at each time step which depends upon heat exchanger's configuration.

$$\varepsilon = \left[\left(\frac{1-\varepsilon_1 \frac{C_{min}}{C_{max}}}{1-\varepsilon_1} \right)^N - 1 \right] \left[\left(\frac{1-\varepsilon_1 \frac{C_{min}}{C_{max}}}{1-\varepsilon_1} \right)^N - \frac{C_{min}}{C_{max}} \right]^{-1} \quad (4)$$

The amount of energy that is needed to raise the inlet water temperature to the required temperature (provided that control signal to the boiler is ON and there is a flow through the boiler) is calculated by using:

$$\dot{Q}need = \dot{m}fluidCpfluid\,(Tst - Tin) \quad (5)$$

If control signal is ON and set temperature is less than inlet temperature, heater will not find negative value of $Qneed$. The energy required is limited by capacity of the boiler. Equation used to determine the amount of fuel utilized by the boiler after calculating the required energy is given as: [3]

$$Qfuel = Qneed/\eta boiler \quad (7)$$

System Performance Indicators

Following performance indicators, based on integrated values of various energies over the whole, optimize the system:

Solar Fraction

$$SF = \frac{\int Q_u}{\int Q_u + \int Q_{aux}} \quad (8)$$

Equation (8) is used to calculate the solar fraction on each collector.

Collector Efficiency

Solar collector efficiency is calculated by:

$$\eta = \frac{\int Q_u dt}{A \int G\, dt} \quad (9)$$

Model Validation

The present model is applied in Trnsys and results are compared with the available experimental and numerical data. It is observed that results of present model are in a good agreement with the past research presented in [4], [6], [7], [8]. The comparison of collector efficiency for both configurations for ETC and FPC was done with [4]. Similarly simulation results of [6], [7] showed that optimum angle is 12° for maximum solar heat gain for the location under consideration and simulation results of [8] for optimal study of a solar air heating system with pebble bed energy storage verify the trend for solar collector area vs solar fraction.

III. RESULTS AND DISCUSSIONS

Simulations were performed in TRNSYS from 0 hour i.e. 1st hour of 1st January till 8760 hr. i.e. last hour of 31st December and Simulation time step is 0.125 hr.

A. *Variation of Solar Fraction with Collector Area and Collector Tilt*

Fig. 2 exhibits the effect of varying ETC area and tilt angle on SF. Maximum value of SF is achieved at 14° tilt angle for each value of solar collector area. Increasing tilt angle further causes SF to decrease. As collector area increases SF increases. Maximum value of SF is achieved at 14° tilt angle for each value of solar collector area. Increasing tilt angle further causes SF to decrease.

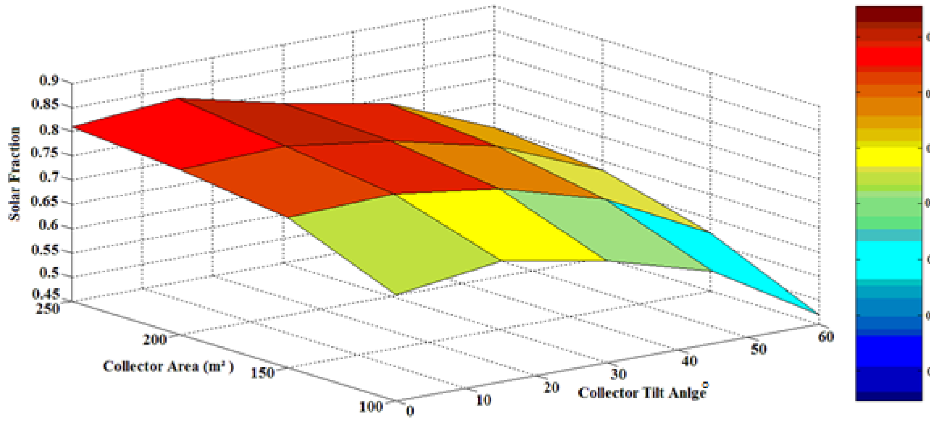

Figure 2: slope, Area vs solar fraction

B. Collector Efficiency

Figure 3 presents monthly thermal efficiency of FPC and ETC for both configurations corresponding to FPC and ETC areas of 68.14 m² and 50 m² respectively. It is evident that ETC yields higher monthly efficiency than FPC, however the effect of system configuration (C-I or C-II) on collector efficiency is marginal. It is also observed that for fixed collector areas of 68.14 m² and 50 m², system without HWST has higher values of collector thermal efficiency. It is because that temperature of the water entering the array of solar collector in a system without HWST is comparatively lower as water entering in the solar collector from HWST.

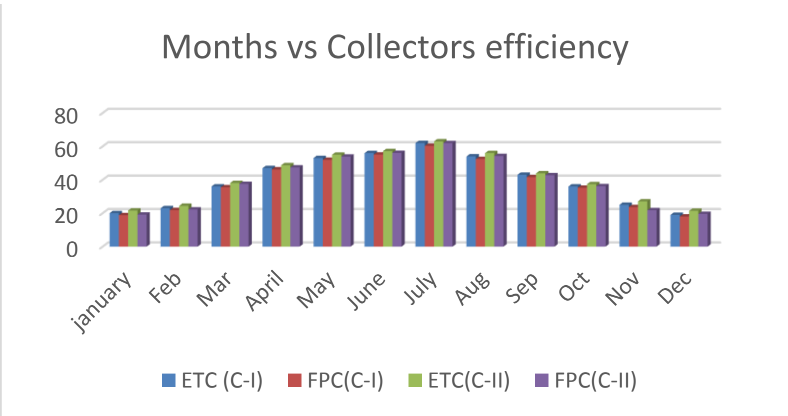

Figure 3: Months vs Collector's efficiency

C. Variation of solar Fraction with respect to Storage Tank size

Figure 4 and 5 shows variation of with respect to specific storage volume for both configurations corresponding to ETC areas of 50 m², 70 m² and 100 m². C-II has higher SF than C-I. Moreover, for any solar collector Area, solar fraction increases as storage tank size increases up to 30 L/m². By further increasing size of storage tank, solar fraction decreases by increasing solar collector area. This is also valid for FPC.

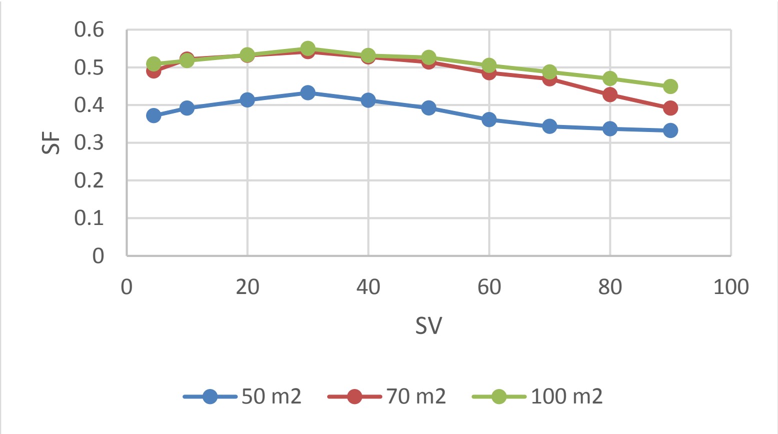

Figure 4: Variation of solar Fraction with respect to Storage Tank size for C-I

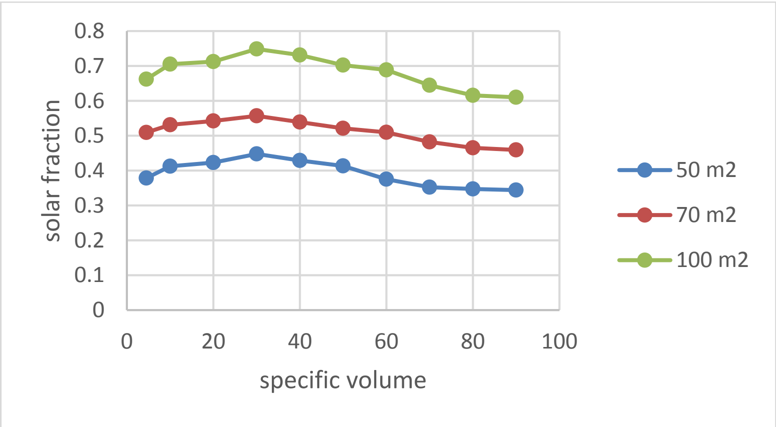

Figure 5: Variation of solar Fraction with respect to Storage Tank size for C-II

D. *Most suitable Organic fluid for targeted output:*

The table 1 shows that the organic fluid R125 is the best option amongst all as it requires least collector area i.e. 50 m² to obtain the targeted output i.e. 1KW.It is also suitable option if we consider the quality of steam at turbine outlet as Tout for R125 which is higher. This shows that it is comparatively drier and is least damaging to turbine blades. Moreover, it requires minimum optimum storage. Lastly, R245ca has maximum efficiency amongst all.

TABLE 1: PERFORMANCE COMPARISONS OF DIFFERENT ORGANIC FLUIDS

Substance (Fluid)	Tout (°C)	ηth (%)	Ac (m²) for ETC	Ac (m²) for FPC	Storage Tank size (liters)	Substance (Fluid)
R125	89.45	3.36	50	68.14	1350	R125
R218	81.78	7.5	58.24	83.17	1570	R218
R236ea	55	12.83	63	87.4	1700	R236ea
R245ca	51.54	12.83	68.12	92.3	1832	R245ca

CONCLUSIONS

This paper presents the modelling and optimization of two system configurations of solar assisted ORC system for Islamabad (33.71° N, 73.06° E). Simulations of the system are done in TRNSYS for the whole year to investigate the possibilities of driving ORC with low grade heat, i.e. from an evacuated tube or flat plate solar collector. Results of the analysis showed that for the given collector area, highest solar fraction is achieved at collector tilt of 14°.Simulation results showed that C-II gives comparatively higher collector thermal efficiency and same trend was observed for FPC. Moreover, efficiency of ETC is higher than FPC. R125 and R245ca emerged as good fluids owing to the least collector area (50 m² for ETC and 68.14 m² for FPC) for desired output i.e. 1KW and maximum fluid efficiency i.e. 12.8 3% respectively. Corresponding to these areas optimized size of HWST is estimated to be 1350 litters. The thermal efficiency for ETC at 50m² is higher as compared to FPC at an area of 68.14 m². Increasing the collector area improves the solar fraction remarkably but its rise decreases gradually after 70 m².R125 requires least storage tank size i.e. 1350 L for desired output. Increasing the specific storage volume above 30 L/m² has no significant effect on solar fraction rather the solar fraction is adversely affected, particularly after 90 L/m² due to heat dissipation of the storage tank. It is also concluded that if system has to be installed without HWST then solar collector area must be increased for the purpose of achieving SF similar to that of system with HWST. The optimum ratio between storage volume and collector area increases as the collector area increases. Therefore, a trade-off between heat collection and heat loss has to be made while attempting to increase solar fraction by improving collector area.

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