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*Research Article*

# Waste heat recovery using Organic Rankine Cycle in Polymer Electrolyte Membrane Fuel Cells

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***Abstract***

*Polymer electrolyte membrane fuel cell (PEMFC) is a viable energy candidate that can be used to replace fossil resources. This paper presents the waste heat recovery in PEMFC using Organic Rankine Cycle (ORC) simulated using MATLAB/SIMULINK platform. R245fa is the working fluid used for recovery of waste heat. The steady state power output of a 100-cell stack is utilized for heat recovery. The maximum power point of the stack at 30 A and 0.41 V is considered for the calculation of net efficiency, after heat recovery. After the simulation, the combined system's efficiency increased by 29.5%.*

***Keywords:*** *Energy utilization; Organic Rankine Cycle (ORC); Polymer Electrolyte Membrane Fuel Cell (PEMFC); Waste heat recovery.*

## 1. Introduction

The increased use of conventional sources of energy entails the establishment of reliable and environmentally beneficial alternatives. Polymer Electrolyte Membrane Fuel Cells (PEMFCs) present an eco-acceptable way of energy production, since they are zero emission technologies. In a PEMFC, the electrochemical reaction of hydrogen and oxygen generates electrical energy. These systems outperform other categories of fuel cells because of their high energy density, fast start-up, and low operating temperature.

Increasing the net efficiency of any power generating process is a fundamental issue to be addressed, when wide commercialization is needed. The efficiency of PEMFC systems can be approximated to 60%. This corresponds to the energy loss of 40%. This dissipated heat energy, can be recovered using proper methodology. This paper presents waste heat utilization in PEMFC systems using Organic Rankine Cycle. The implementation of recovery system has been simulated using MATLAB/SIMULINK. Most studies in literature focus on efficiency enhancement in PEMFC using chemical and physical modifications within the power-plant. The integration of an ORC to recover heat energy from PEMFC using R245fa and the efficiency calculation at the maximum power point is outlined in this work.

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The aim of this study is to formulate energy efficient methods to aid the advancement of green energy technologies. [1] Affirms the importance of energy management in PEMFC, and uses dynamic power rating in the system for analysis. Organic Rankine Cycle can be used along with solar power-plants, geo-thermal systems, biomass and combustion systems for heat recovery [2]. Their work addresses the thermodynamic feasibility of Organic Rankine Cycle for heat recovery from low temperature sources. [3] embodies the usage of ORC with solar based systems in converting thermal energy to electrical energy. This energy is used to power desalination system for water treatment. In their work, working fluid used for ORC is R-245fa. The highlight of the paper is the development of a numerical model for ORC implementation. The power produced on using an ORC is estimated using deep learning algorithms and stepwise multi-linear regression in [4]. The method seems to be effective for implementation of efficient ORC in-line with various power-production systems. The usage of ORC with various working fluids was the subject of [5–7]. [5] Draws our attention to focus on working fluids R-1233zd (E) and R-1224yd (Z) to replace conventional ORC working fluids. The paper considers the compatibility, power and efficiency during implementation of these working fluids. Their approach seems to be well grounded and plausible. The working fluids R-32, R-407A, R-422C and R-134a for

ORC is analyzed in [6]. Thermal efficiency comparison for these working fluids at different boiler exit temperatures and condenser settings is a highlight of their work. [7] Suggest using R-1233zd with lower global warming potential in ORC. A key problem with much of the literature on ORC is that, the implementation in association with fuel cell power plant is not discussed. This has lead authors [8] to investigate ORC implementation with PEMFC. This work establishes steady state and dynamic models of PEMFC and integrates an ORC with the simulation. But the working fluid is not specifically mentioned and they are taking a zeotropic mixture for the simulation. A combined PEMFC-ORC system is modeled in [9]. The work also analyses the effect of different operating conditions and working fluid in the overall system performance after adding ORC.

The current work deals with using ORC with PEMFC power system for enhancing the combined system efficiency. For making this integration realistic, the steady state plant data at 50% efficiency is directly taken for the calculation. The PEMFC model described in [10] is used for simulating the heat recovery system. The efficiency of the integrated system calculated from experimental data and simulated model are remarkably similar. The novelty of the work is geared towards the efficiency improvement of the combined system, analyzed in both experimental and simulation perspective.

## 2 Materials and Methods

The steady state power output of PEMFC, working at 68.7° C is used for deriving the recovery methodology. The steady state plant data obtained from Vikram Sarabhai Space Centre, Trivandrum is captured for the analysis. In this work, waste heat recovery is posed in terms of the PEMFC model described in [10]. We opted for this particular operating temperature, since the efficiency of the system was found to be 49.97%, which is very close to 50%. Figure 1 shows the power and voltage plots of PEMFC at 68.7⁰C. The data gathered was plotted in OriginPro 8.5[11].

The same power-plant is simulated by the authors in [10], which is used for implementation of the heat recovery system in MATLAB-2019a.

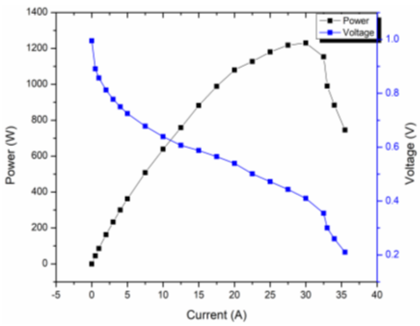


**Figure 1:** Steady state power output of PEMFC stack

## 3. Waste heat recovery

The waste heat generated in a PEMFC stack of 100 cells is accounted in terms of the power produced. To mathematically represent this, the plant data at 50% efficiency is taken. At this efficiency, the heat generated by the system will be mathematically equal to the power. This heat energy is to be recovered to enhance the net performance of the system.

### *3.1 Organic Rankine Cycle*

Since PEMFCs represent systems which reject heat in low temperature ranges, an Organic Rankine Cycle will be the best choice [12]. The basic block diagram representation of an ORC, integrated to a PEMFC system is as shown in Figure 2. Heat recovery systems using thermoelectric generators (TEG) is also another concept that could be implemented [13]. But the installation cost is comparatively high for TEG. At any operational level, systems integrated to boost net efficiency must not result in a substantial loss of performance. The benefits of ORC in terms of efficiency far outweigh the disadvantages with regard to the number of subsystems utilized for implementation. It has been suggested that [14] using R-245fa as working fluid gives maximum net power than R-123 and R-134a. This work also examines the use of heat pump combined ORC. [15] gives the performance analysis of an ORC integrated PEMFC during off-design working. The optimized operating conditions for the hybrid system is also described in their work.

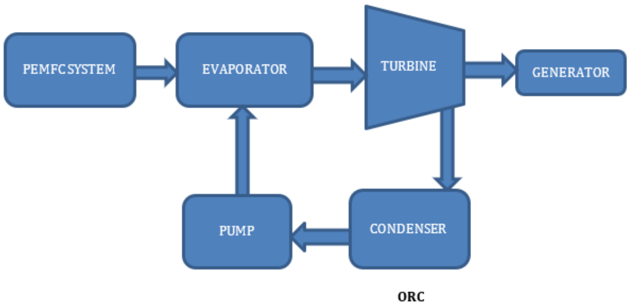


**Figure 2:** Block diagram representation of PEMFC integrated with an Organic Rankine Cycle

[16] compares the performance of ORC using different working fluids and operating conditions.[17] demonstrates a comparison of integrating gas turbine to PEMFC and ORC to PEMFC. They outlines exergy, energy and economic analysis of both systems. Their findings indicate that gas turbine systems are more efficient and economic than ORC. A growing body of literature [18] has investigated the use of ORC with steam power plants.

#### *3.1.1PEMFC System*

The system under consideration is adopted from PEMFC stack, consisting of 100 cells. The stack is operating at a temperature of 68.7˚C. The power produced from the stack approximates to 1.2kW. The steady state power output is taken as the criteria for comparing performance before and after integration of ORC.

*3.1.2.Evaporator*

As current is drawn from the fuel cell stack, heat energy is produced at its outlet. This heat energy is extracted by the evaporator, which transfers the energy to the pressurized fluid pumped by the pump. Thus the fluid is superheated, isobarically, with phase change in the evaporator.

*3.1.2.Turbine*

The turbine receives superheated steam from the evaporator. At constant entropy, expansion takes place in the turbine. Thus, the rotating turbine blades transfer this mechanical energy onto the generator.

*3.1.3.Generator*

The turbine is coupled with a generator, to produce electrical energy. The motive power of turbine is used to extract electrical power as generator output.

*3.1.4.Condenser*

The working fluid coming as turbine outlet is condensed by the condenser. At constant pressure, heat exchange with a cold fluid happens here.

*3.1.5. Pump*

The pump pressurizes the working fluid and transfers this fluid to the evaporator. The process is taking place isentropically.

*3.2 ORC Calculations*

To implement an ORC in association with PEMFC, the thermodynamic properties of the working fluid is required. The temperature-entropy diagram of R-245fa is shown in Figure 3. The enthalpies and entropies corresponding to the points indicated in the T-S diagram is to be calculated for ORC implementation.

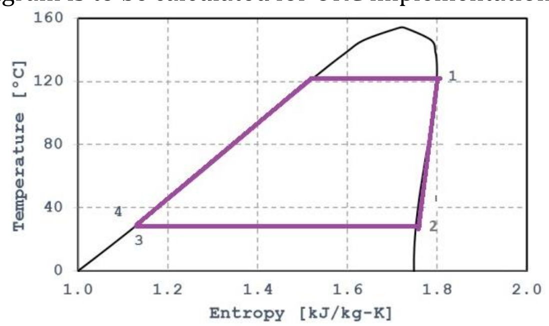


**Figure 3:** T S diagram of R-245fa [19]

The T-S diagram of PEMFC indicates that the critical point of R-245fa is 427 K, where phase boundaries are absent. The boiler is proposed to work with exit temperature of 433K. The corresponding pressure to which fluid is raised is 33.3 bar. To calculate the enthalpies and corresponding entropies, the database COOLPROP is called to MATLAB-2019a platform. The mass flow rate of liquid is 1 kg/s. The enthalpies and entropies at points 1,2,3, and 4 in the T-S diagram is captured through COOLPROP database and is shown through equation(1) to equation(6).

$$h_1 = 5.13 * 10^5 \ J/kg \quad \text{.......(1)}$$

$$s_1 = 1.85 * 10^3 \ J/K \quad \text{.......(2)}$$

$$T_2 = 298 \ K \quad \text{.......(3)}$$

$$h_2 = 4.2 * 10^5 \ J/kg \quad \text{.......(4)}$$

$$h_3 = 2.32 * 10^5 J/kg \quad \text{.......(5)}$$

$$h_4 = 2.35 * 10^5 \ J/kg \quad \text{.......(6)}$$

$$\text{Heat Input} = \text{Mass flow rate of ORC } (h_1 - h_4) \quad \text{.......(7)}$$

The turbine and pump working in ORC is not considered to be completely efficient. The turbine efficiency is taken as 92 % and pump efficiency to be 89 %.

$$\text{Turbine work} = \text{Mass flow rate of ORC } (h_1 - h_2) * \text{Turbine efficiency} \quad \text{.......(8)}$$

$$\text{Pump Work} = \text{Specific volume} \frac{(P_4 - P_3)}{\text{Pump efficiency}} \quad \text{.......(9)}$$

$$\text{Shaft output power} = \text{Turbine work} - \text{Pump Work} \quad \text{.......(10)}$$

The efficiency of Organic Rankine Cycle is calculated as the ratio of shaft output power to input heat received by the cycle.

$$\text{Cycle efficiency} = \frac{\text{Shaft output power}}{\text{Heat Input}} \quad \text{.......(11)}$$

Borello [20] affirms that integrating an ORC with PEMFC increases the efficiency of whole power generating system.

*3.3 ORC Implementation in Simulink*

To compare the ORC implementation with the steady state model of PEMFC, the model proposed by the authors [10] is used. The model is simulated for the experimental values of input current. This gives voltage output. From these values of voltage and current, power output is evaluated for a 100 cell stack. Taking this power output as the heat input to ORC, simulation is done. To simulate this entails assuming that the stack is working at 50% efficiency. The equations (1) to (11) is used for calculating net efficiency of the system. Figure 4 describes ORC implementation in Simulink platform. To the same schematic, experimental voltage and current values are initially fed, to yield net output power.

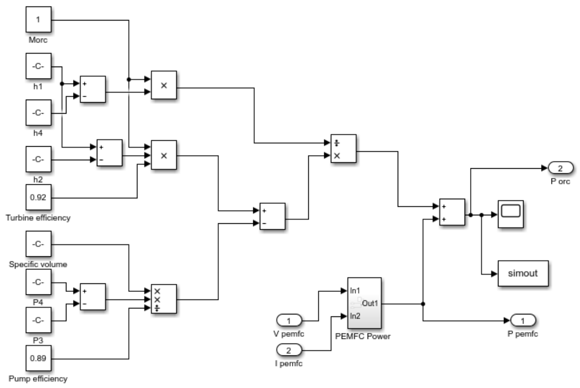


**Figure 4:** Implementation of ORC in SIMULINK

The system is then fed with simulated voltage and current values of [10] also. This gives the simulated power output of the system. The experimental and simulated power output are compared in Figure 5.The figure indicates coinciding plots when simulation and experimental heat recovery is done.

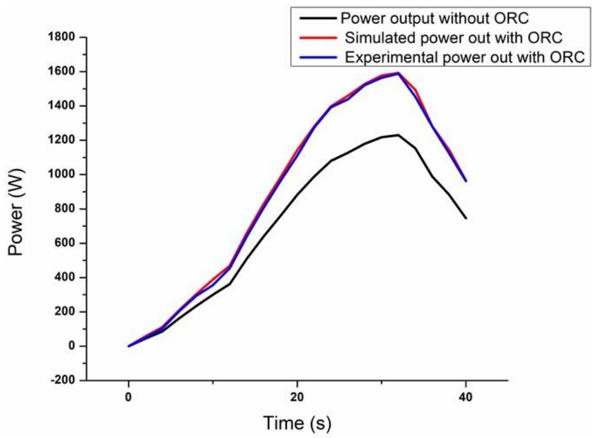


**Figure 5:** Power plot comparison

### *3.4 ORC Efficiency Improvement*

On using ORC as a bottoming system to PEMFC power-plant, the combined efficiency of the system gets added up. This is outlined in this section. The work done by turbine is calculated from (8) as given in equation (12).

$$\textbf{Turbine Work} = 8.24 * 10^4 \ \textbf{J/kg} \qquad (12)$$

From (10), the output power of shaft is calculated as (13)

$$\textbf{Shaft Output Power} = 7.98 * 10^4 \ \textbf{J/kg} \qquad (13)$$

Using equation (7), heat input to the system can be calculated as in (14).

$$\textbf{Heat Input} = 2.7 * 10^5 \ \textbf{J/kg} \qquad (14)$$

The ORC efficiency is calculated from (11) as in equation (15).

$$\textbf{Cycle efficiency} = \frac{\textbf{Shaft output power}}{\textbf{Heat Input}} = 0.295 \qquad (15)$$

This result has further strengthened our confidence on adding up an ORC as bottoming cycle with a PEMFC power plant. Converting the efficiency to percentage, the ORC system is 29.5% efficient. The PEMFC system without ORC has the maximum power point at 1230W. With the Organic Rankine Cycle, the system has power output of 1592.85 W. Mathematically, this accounts to 29.5% efficiency.

## 5. Simulation results and discussion

Our research underlines the importance of integrating an Organic Rankine Cycle at PEMFC outlet. The steady state plant data as depicted in Figure 1 is used as the input to ORC heat recovery system. The implementation of ORC using equations (7) to (11) is done after capturing the thermodynamic properties of working fluid R-245fa, through COOLPROP database. The enthalpies and entropies of working fluid are outlined in equations (1) to (6). The power output of the simulated model, with and without ORC is compared with experimental data driven heat recovery system. This power outputs are illustrated in Figure 5. Noteworthy differences were not found between experimental and simulated methods of heat recovery. The efficiency of the prepared ORC was calculated considering equation (11). The net cycle efficiency of ORC is obtained as 29.5%. The efficiency improvement at the maximum power point of experiment conducted is calculated. At the maximum power point, the steady state power was enhanced from 1230 W to 1592.85 W.

## Conclusions

The evidence from this work points towards the idea of implementing ORC with PEMFC power system. Our contribution's strength resides in the integrated system's increased efficiency. The proposed heat recovery concept has the potential to be a powerful tool for assisting the energy sector. These findings, in our opinion, are a fantastic first step toward extracting maximum energy from the PEMFC system while using fewer interconnected subsystems. On using an organic Rankine cycle in outlet of PEMFC, the heat energy otherwise lost is partially recovered efficiently with an efficiency increase of 29.5%.This substantiates previous findings in literature that an ORC can be integrated to various categories of power-plants [21]. Our approach would lend itself well for use by various other working fluids also.

### *6.1 Limitations and future Implications*

The present work is constrained in some aspects. Generalization of the procedure requires further investigations. Modifications of ORC in thermodynamic aspects has been the matter of some recent studies [22]. Thermodynamic modifications of ORC and exergy analysis are not considered in current work. We were unable to investigate optimization of parameters of ORC, integrated to PEMFC. ORC parameters are optimized using response surface methodology in [23].

Despite this, we believe our work could be a framework for implementing an effective energy recovery system for PEMFC. Future studies on the current topic are suggested in order to establish more effective working fluids in ORC and other methods of improved thermal efficiency.

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