



## More about Thermosyphone Rankine Cycle Performance Enhancement

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### ABSTRACT

The heat pipe applications have been coupled with the renewable energy sources such as solar energy, waste heat and geothermal energy. Thermosyphon Rankine Cycle (TRC) is a vertical wickless heat pipe engine. In this engine, the turbine is installed between the insulated section and a condenser section of thermosyphon. The mechanical energy developed by the turbine can be converted to electricity by direct coupling to an electrical generator. Our simulation results showed that the enhanced TRC model is able to increase the efficiency of the TRC system. This paper introduces the miscellaneous new ways in order to improve the performance of a TRC system for supplying the sustainable electricity. For example, a 0.78% increase in the turbine useful efficiency due to the superheating process was obtained.

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### NOMENCLATURE

$h$	Specific enthalpy (kJ/kg)	$T_{evap,source}$	The evaporator source temperature ( $^{\circ}C$ )
$k_B$	Turbine blade ratio speed	$T_4$	The superheated temperature ( $^{\circ}C$ )
$M_5$	Nozzle outlet Mach number	$T_{4,max}$	The maximum value of $T_4$ ( $^{\circ}C$ )
$M_{5,max}$	The maximum value of $M_5$	$T_c$	The ambient temperature ( $^{\circ}C$ )
$N$	Turbine rotor speed (rpm)	<b>Greek Symbols</b>	
$N_{Lim}$	Turbine rotor limited speed (rpm)	$\alpha$	inlet blade angle
$\dot{Q}_e$	The input heat flux of TRC system (W)	$\gamma$	outlet blade angle
$R_{Turbine}$	Radius of the turbine rotor (m)	$\eta_{Carnot}$	Carnot cycle efficiency (%), $\eta_{Carnot} = 1 - T_c / T_{evap,source}$
$Ratio_{eff}$	Means as: $\eta_{ut} / \eta_{Rankine}$	$\eta_{Rankine}$	Rankine cycle efficiency (%), $\eta_{Rankine} = W_{Turbine} / Q_{evap,source}$
$Ratio_N$	Means as: $N / N_{Lim}$	$\eta_{ut}$	Turbine useful efficiency (%)
$T_e$	The evaporator temperature ( $^{\circ}C$ ), $T_e = T_2 = T_3$	$\eta_{II}$	Second law efficiency (%)

## 1. INTRODUCTION

Environment protection tends to low emissions of carbon oxides and sulphur oxides, zero ozone depletion potential and low global warming potential. The alternative pathway towards a low carbon economy leads to a high degree of electrification, particularly in the transport and heating sectors [1]. Except the low

carbon lemma, the energy system can only be considered sustainable in the long term if it is affordable and secure. Affordability of energy means that the cost of electricity is acceptable by consumers; security of supply indicates that the new energy is provided continuously and sustainably [2, 3].

Up to now, the most active power plants have increased in size [4]. Therefore, they have been inevitably centralized and built far from urban areas. Thus, electricity loss occurs during distribution. As a result, the located urban power generation systems are

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of considerable importance. Therefore, for these small power systems, the low-temperature heat sources such as solar energy, waste heat and geothermal energy can be selected. Using conventional methods to recover energy from this kind of energy sources is economically infeasible. Therefore, it is important to develop an economically efficient system that can generate power and/or electricity from low-temperature heat sources.

In recent years, organic Rankine cycle (ORC) has become a field of intense research and appears a promising technology for conversion of the low-temperature heat into useful work or electricity [5-7]. In an ORC system, instead of water, an organic fluid with a lower boiling temperature is used as working fluid. The ORC system employs expander to generate the work. The expander is a critical component limiting the cycle efficiency, especially in the low-temperature region (less than 100 °C). Two main types of expanders can be distinguished: the dynamic type, such as the axial reaction turbine expander, and displacement type, like the screw, the scroll and the vane expanders [8].

The results for a reaction turbine showed that the highest efficiency happens at the turbine infinite speed [9]. If turbo expanders and screw expanders are scaled down to 10 kWe level, their efficiencies are likely to become unacceptable because they are commonly designed for larger units and high pressure and temperature operations. Micro-scale turbo expanders and screw expanders (1-10 kWe) are currently under development with the aim of increasing efficiency and reducing costs [3].

Scroll and Vane expanders are relatively easy to be scaled down in a wide range of 1-10 kWe, in comparison with the micro turbines. Tahir et al. [10] described the experimental efficiency of a compact ORC system with a compact rotary vane type expander. In their works, approximately 30 W of expander power output with 48% expander efficiency and 4% thermal efficiency of ORC system (with a temperature difference between the hot and cold sources of 80°C) were actually achieved. Although, in a vane expander, the isentropic efficiency increases with increasing rpm (rotation per minute) of the vane expander, but Tahir et al. tests showed that the performance vs. rpm curve had a peak output in the specific rotation of the vane expander (see Figure 1). This means that the maximum efficiency of a vane expander may be actually limited to the specific rpm, which means it is the troublesome work to deliver the highest performance by this device. In the same way, in order to use the low temperature (<150°C) solar energy source, Saitoh et al. [11] experimentally resulted and declared that the ORC solar system is not unrealizable in photovoltaic (PV) cell systems. Hence, this system is expected to be used for small distributed power generation system in the future.

Thermosyphon Rankine cycle system is an environmentally friendly system for direct extraction of

electrical power using low enthalpy heat sources (specifically less than 100°C since the inside air system has been evacuated). TRC system is a vertical wickless heat pipe (i.e. one two-phase closed thermosyphon). In this engine, an impulse vapor turbine has been installed between the adiabatic and the condenser sections and is capable of converting high kinetic energy of vapor in the pipe to electrical energy by using a directly coupled electrical generator (see Figure 2). The primary TRC tests gave the low efficiencies about  $\eta_i=0.21\%$  for this engine when the turbine rotated at 3750 rpm [12]. Later, Ziapour [13] recommended an enhanced design of the TRC system using impulse turbine. He formulated the energy and the exergy analysis of this enhanced TRC system in order to estimate its optimum operating conditions. The results showed that the highest efficiency happens for an impulse turbine at the turbine limited speed (i.e.  $N_{Lim}$ ). Then the lack of actual efficiency of a TRC system (i.e.  $\eta_i=0.21\%$ ) was interpreted by using  $N_{Lim}$  as follows: By assuming water as working fluid, then the value of  $N_{Lim}=78168.07$  (rpm) is obtained for the test prototype. Therefore, the turbine rotation deviation from the Rankine operation is  $78168.07-3750=74418.07$  (rpm). In fact, these big deviations result in small efficiencies. Finally, the simulation results indicated that the enhanced TRC model could be able to increase the efficiency of the TRC system.

The aim of this paper is to find the optimum operating conditions for the TRC system through thermodynamic analysis of this cycle system. The effects of the superheating process on a TRC cycle system thermal efficiency are preferably discussed in this paper.

## 2. THE IMPROVED TRC SYSTEM

In a simple TRC system consisting of a single tube (see Figure 2), thermal performance is restricted by entrainment and flooding phenomena. Furthermore, it is difficult to maintain a uniform liquid film which causes the heat transfer performance to deteriorate. The flooding phenomena can be solved by using a loop type TRC system where vapor and liquid flow passages are separated. The loop type TRC system had been recommended in the prior work [13]. In the present work, the loop type TRC system has been improved using the added superheating processes, as shown in Figure 3. T-s diagram of this improved TRC system is shown in Figure 4. Also, the steam drum (or pool) type evaporator has been selected instead of the showering nozzle type evaporator. This type evaporator can be suitable for receiving the renewable energy need via the flow boiling process. Schematic presentation for providing the energy need by using the flow boiling

process is shown in Figure 5. It is found that the flow boiling process has beneficial heat transfer characteristics. In addition, in order to provide the supersonic vapor flow for the blades of the impulse turbine, a convergent-divergent nozzle (processes 4 and 5) has been used after the superheating process (processes 3 and 4), as shown in Figure 3. In order to describe the performance characteristics of the improved TRC system, then the three custom quantities as  $\eta_{II}$ ,  $\eta_{Rankine}$  and  $\eta_{ut}$  have been selected for showing the thermodynamic second law, the Rankine and the turbine useful efficiencies, respectively [13].

### 3. RESULTS AND DISCUSSIONS

Based on the energy balances for the improved TRC cycle processes (as shown in Figure 3), a steady-state simulation program for this cycle system was developed using EES (Engineering Equation Solver) software which contains the thermodynamic properties of a variety of fluids and refrigerants. Without the superheating process, then the model of the improved TRC cycle was validated with the prior work. The comparisons depicted that the results obtained from the present model were equal in every respect as the prior cited work [13].

In the work of Ziapour [13], the turbine rotor limited speed ( $N_{Lim}$ ) was calculated in the case as:  $\alpha=\gamma=0$ . where  $\alpha$  and  $\gamma$  are the inlet and the outlet turbine blade angles respectively. These angles are shown in Figure 6. In present study, the values of these quantities have been selected identically but not zero (i.e.  $\alpha=\gamma$ ). With considering this new condition for  $\alpha$  and  $\gamma$ , then the following new formula is obtained for  $N_{Lim}$  as [13]:

$$N_{Lim} = \frac{1}{R_{Turbine}\pi} \sqrt{\frac{450(h_4 - h_1)\eta_{Rankine}}{\left(\cos^2 \alpha - \frac{1}{2}\right) \left[ 1 + \frac{k_B \cos \gamma}{\cos \alpha - \frac{1}{2\cos \alpha}} \sqrt{\left(\cos \alpha - \frac{1}{2\cos \alpha}\right)^2 + \sin^2 \alpha} \right]}} \quad (1)$$

variation of  $N_{Lim}$  vs. the radius of the turbine rotor ( $R_{Turbine}$ ), for different values of  $\alpha$  and  $\gamma$  are shown in Figure 7. It is seen that with increasing  $R_{Turbine}$  and decreasing  $\alpha$  (and  $\gamma$ ), then  $N_{Lim}$  decreases. As shown from Figure 7, one can see that maximum and minimum values for  $N_{Lim}$  happen at  $\alpha=\gamma=0$  and  $\alpha=\gamma=60^\circ$  respectively. The radius of the turbine, the ambient temperature and the input heat flux of TRC system were  $R_{Turbine} = 0.4m$ ,  $T_\infty = 25^\circ C$  and  $Q_e = 1kW$  respectively.. Also, the evaporator source temperature ( $T_{evap,source}$ ) is assumed be:  $T_{evap,source} - 10 = T_2 = T_3$ .

The second law of thermodynamic efficiency ( $\eta_{II}$ ) and the turbine useful efficiency ( $\eta_{ut}$ ) vs.  $\alpha=\gamma$  are shown in Figure 8. As shown, these efficiencies decrease when the values of  $\alpha$  and  $\gamma$  increase. In the case of  $\alpha=\gamma=60^\circ$ , these values are close together and tend to zero.

If the impulse turbine rotor turns at the speeds below the limited speed ( $N_{Lim}$ ), then the useful efficiency decreases. This case is clearly shown in Figure 9. This figure shows the effects of the  $Ratio_{eff}$  in comparison to the  $Ratio_N$ , for different values of  $\alpha=\gamma$ . Here,  $Ratio_N$  is the ratio of the actual turbine rotor speed ( $N$ ) to the turbine limited speed ( $Ratio_N = N/N_{Lim}$ ). Also,  $Ratio_{eff}$  is the ratio of the turbine useful efficiency to the turbine Rankine efficiency (i. e.  $Ratio_{eff} = \eta_{ut}/\eta_{Rankine}$ ). It seems that these curves act as design curves for selecting the optimal values of design parameters. For example, if  $Ratio_N = 0.1$ , then the value of  $Ratio_{eff}$  for  $\alpha=\gamma=0$  and  $\alpha=\gamma=50$  are 0.19 and 0.23, respectively.

Variation of the superheated vapor temperature ( $T_4$ ), vs. evaporator source temperature ( $T_{evap,source}$ ) is shown in Figure 10. We correlated the curve of Figure 10 as follows:

$$T_4 = -149.043 + 4.16715T_{evap,source} + 0.00532309T_{evap,source}^2 \quad (2)$$

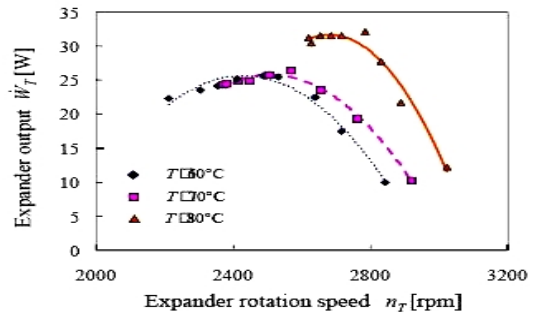


Figure 1. Relationship between rotary vane expander power and rotation speed for different temperature  $\Delta T$ (temperature difference between the hot and cold sources) as:  $\Delta T = 60^\circ C$ ,  $70^\circ C$ , and  $80^\circ C$

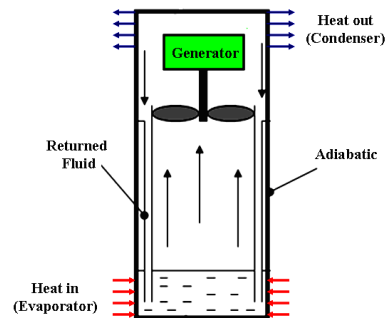


Figure 2. Schematic presentation of a simple TRC system

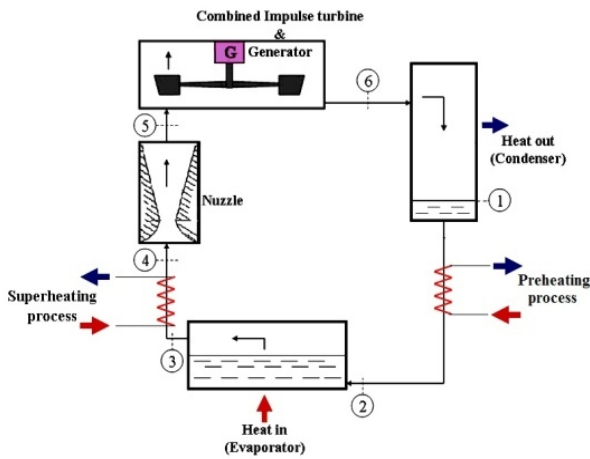


Figure 3. Schematic presentation of an improved TRC system

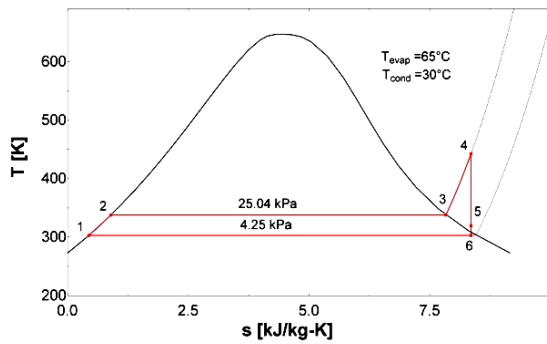


Figure 4. T-s diagram of the improved TRC system

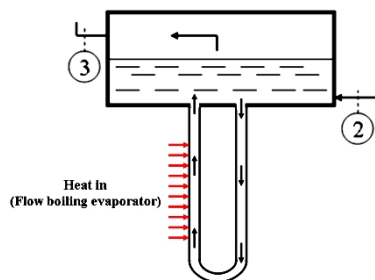


Figure 5. Receiving solar, geothermal or waste heat energy using the flow boiling mechanism

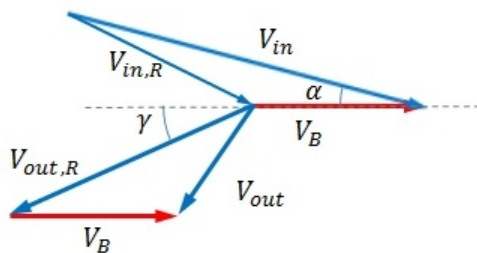


Figure 6. The vectors related with angles of  $\alpha$  and  $\gamma$

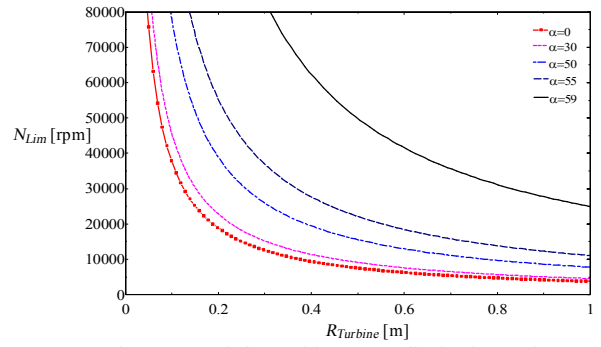


Figure 7. The curve of the turbine rotor limited speed ( $N_{Lim}$ ) vs.  $R_{Turbine}$  for different values of the inlet and outlet blade angles ( $\alpha=\gamma$ )

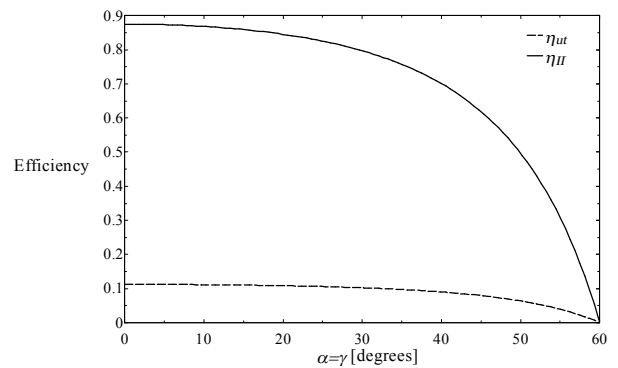


Figure 8. The curves of the second low and the useful efficiencies vs. the inlet and outlet blade angles ( $\alpha=\gamma$ )

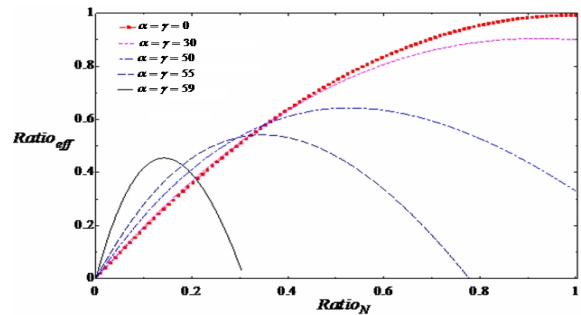


Figure 9. The curve of  $Ratio_{eff}$  vs.  $Ratio_N$  for different values of  $\alpha = \gamma$

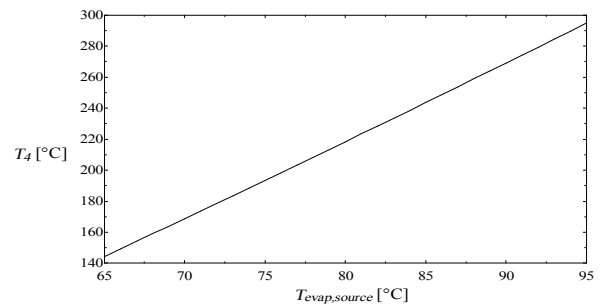
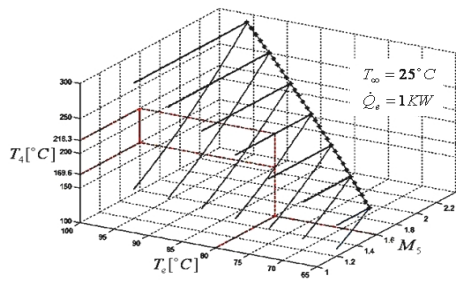
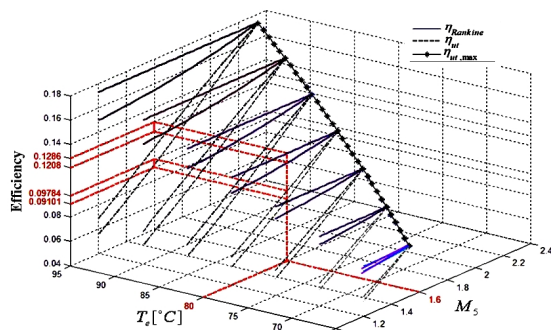


Figure 10. The curve of the superheated vapor temperature ( $T_4$ ) vs. the evaporator source temperature ( $T_{evap,source}$ )



**Figure 11.** The curve of the superheated temperature ( $T_4$ ) vs. the evaporator temperature ( $T_c$ ) and the nozzle outlet Mach number ( $M_5$ )



**Figure 12.** The curves of the TRC cycle system efficiencies vs. the evaporator temperature ( $T_c$ ) and the nozzle outlet Mach number ( $M_5$ ).

As shown in Figure 11, one can see that for evaporator temperature at  $T_c=80^\circ\text{C}$ , there are low and high boundaries of the superheated vapor temperature which  $T_4$  can fluctuate within these limits. In this condition, the extreme values for the nozzle outlet Mach number ( $M_{5,\max}$ ) and the superheated vapor temperature  $T_{4,\max}$  are obtained as:  $M_{5,\max}=1.96$  and  $T_{4,\max}=218.33^\circ\text{C}$ . Also, for this condition, as shown from dashed lines in Figure 11, at the nozzle outlet Mach number as:  $M_5=1.6$ , the lower boundary of the superheated process is as  $T_4=169.6^\circ\text{C}$  and the higher boundary is as  $T_4=218.30^\circ\text{C}$ . In Figure 12 the lower and higher boundaries of both the Rankine and the useful efficiencies have been distinguished (see dashed lines). These depict that in the conditions:  $T_c=80^\circ\text{C}$  and  $M_5=1.6$ , the share of the superheating process on the efficiencies increasing is  $12.86-12.08=0.76\%$  for the Rankine efficiency ( $\eta_{\text{Rankine}}$ ), and  $9.78-9.10=0.78\%$  for the turbine useful efficiency ( $\eta_{\text{ut}}$ ). Finally, optimization is playing the main role in many engineering problems. In order to optimize the performance functions of a TRC engine, an improved optimization method such as multi-objective genetic algorithm were applied [14].

#### 4. CONCLUDING REMARKS

In order to reduce the greenhouse gas emissions, the located urban power generation systems are of considerable importance. For these small power systems, the low-temperature heat sources such as solar energy can be selected. In order to use the low temperature ( $<150^\circ\text{C}$ ) solar energy source, the ORC solar system is not unrealizable in photovoltaic (PV) cell systems. TRC system is an environmentally friendly system for direct extraction of electrical power using low enthalpy heat sources, specifically less than  $100^\circ\text{C}$ . Based on the simulation results in this paper, the improved TRC model can increase its efficiency. The following noticeable new results are obtained through the figures and curves:

- With increase of  $R_{\text{Turbine}}$  and decrease of  $\alpha$  (and  $\gamma$ ), then  $N_{\text{Lim}}$  decreases.
- With increase of both  $\alpha$  and  $\gamma$ , then the value of both  $\eta_{\text{II}}$  and  $\eta_{\text{ut}}$  decrease.
- For a specific evaporator temperature, there are low and high boundaries of the superheated vapor temperature which  $T_4$  can fluctuate within of them.
- As an example: In the conditions:  $T_c=80^\circ\text{C}$  and  $M_5=1.6$ , then the share of the superheating process on the efficiencies increasing is  $0.76\%$  for the Rankine efficiency ( $\eta_{\text{Rankine}}$ ) and  $0.78\%$  for the turbine useful efficiency ( $\eta_{\text{ut}}$ ).

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## More about Thermosyphon Rankine Cycle Performance Enhancement

## RESEARCH NOTE

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کاربردهای لوله‌ی گرمایی با انرژی‌های تجدیدپذیر نظیر انرژی خورشیدی، گرمای هدر رونده و انرژی زمین‌گرمایی گره خورده است. چرخه‌ی رانکین ترموسیفونی (TRC) یک موتور لوله‌ی گرمایی قائم و بدون فتیله است. در این موتور توربین بین قسمتهای بی دررو و چگالنده‌ی ترموسیفون نصب می‌شود. انرژی مکانیکی به دست آمده از توربین که مستقیماً با ژنراتور برق درگیر است، به الکتریسته تبدیل می‌شود. نتایج شبیه‌سازی کار حاضر نشان داد که مدلی بهبود یافته از TRC قادر به افزایش‌دادن کارایی سیستم TRC معمولی می‌باشد. این مقاله به معرفی راه‌های متنوع جدید به منظور بهبود دادن به کارایی سیستم معمولی TRC برای تامین الکتریسته‌ی پایدار می‌پردازد. برای مثال، درصد افزایش کارایی مفید توربین در نتیجه‌ی فرایند فوق گرم کردن به میزان ۰/۷۸ درصد حاصل شد.

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