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A THERMAL ANALYSIS OF AN IMPROVED RANKINE STEAM POWER CYCLE

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ABSTRACT

To improve the thermodynamic thermal efficiency (TE) of the basic Rankinesteam power cycle (RC)the average boiler temperatureshould be increased and/or the condenser temperature should be lowered. This paper considers modified RCssuch as (1)RC with reheating, (2) regenerative RC and (3) combinations of (1) and (2). One or more turbines and pumps are included in this analysis. The compression processes of water inside pumps and expansion of steam inside turbines are assumed isentropic. The pressure losses inside the boiler and condenser are ignored. The optimizations of thermodynamic thermal efficiency (TE) of those cycles were carried out under theconstraint ofnon-saturated steam state at turbine outlet(s).Pressure and temperature are the optimization parameters. The results indicate that near-optimal cycles performance may be achieved under certain power cycles layouts.

KEYWORDS: Rankinecycle, Thermodynamic Thermal Efficiency, Optimization

NOTATION

Q	Heat flow per unit mass, Watt/kg
$\dot{m}$	Mass flow rate, kg/s
$\dot{W}$	Mechanical power per unit mass, Watt/kg
η	(TE) Thermodynamic efficiency of the process, dimensionless.
h	Specific enthalpy, J/kg
s	Specific entropy, J/kg.K
p	Pressure, bar.
T	Temperature, ^{o}C
$\bar{T}_h$	Average boiler temperature

INTRODUCTION

The performance of Rankine power cycles relies on the working fluid and sources of thermal energy. Yamamoto et al. [1] proposed an environmentally friendly system called the "Organic Rankine Cycle" (ORC) in which low-grade heat sources are utilized. The working fluid used in their study was an organic substance with a low boiling point and a low latent heat.Liu et al. [2] presented an analysis of the performance of organic Rankine cycle (ORC) subjected to the influence of working fluids. They investigated the effects of various working fluids on both the thermal efficiency and the total heat-recovery efficiency.By using supercritical CO2, Yamaguchi et al. [3] proposed a solar energy powered Rankine cycle for combined production of electricity and thermal energy. The system utilized evacuated solar collectors to convert CO2 into high-temperature supercritical state, used to drive a turbine and thereby produce mechanical energy and hence electricity.Kosmadakis et al.[4] conducted a parametric study of an autonomous, two-stage solar organic Rankine cycle for RO desalination to estimate the efficiency, as well as to calculate the annual mechanical energy available for desalination.Chen et al.[5] reviewed the organic Rankine cycle and supercritical Rankine cycle for the conversion of low-grade heat into electrical power, as well as selection criteria of potential working fluids. Their paper discussed the types of working fluids, influence of latent heat, density and specific heat, and the effectiveness of superheating.Lai, et al. [6] considered alkanes, aromates and linear siloxanes as working fluids for high-temperature organic Rankinecycles (ORCs). They performed case studies using the molecular based equations of state BACKONE and PC-SAFT.

The performance of Rankine cycle may be improved by altering the working fluid type and/or the working temperature. The improvement includes optimization procedure with (an) objective function(s). Hettiarachchi et al. [7] presented a cost-effective optimum design criterion for Organic Rankine power cycles utilizing low-temperature geothermal heat sources. They used the ratio of the total heat exchanger area to net power output as the objective function, which is optimized using the steepest descent method.Desai et al.[8] analyzed 16 different organic fluids as a working medium for the basic as well as modified ORCs. They proposed a methodology for appropriate integration and optimization of an ORC as a cogeneration process with the background process to generate shaft-work.Dai et al. [9] described organic Rankine cycles for low-grade waste heat recovery with different working fluids. They examined the effects of the thermodynamic parameters on the ORC performance. As an objective function, the exergy efficiency was optimized by means of the genetic algorithm.Delgado-Torres et al. [10] presented solar thermal driven reverse osmosis. They considered twelve substances as working fluids of the ORC and four different models of stationary solar collectors (flat plate collectors, compound parabolic collectors and evacuated tube collectors).Jing et al.[11] proposed a design to reduce heat transfer irreversibility between conduction oil and HCFC-123 in the heat exchangers of and organic Rankine cycle with stability of electricity output maintained. Teyssedou et al.[12] presented a multi-objective optimization method that permits solutions, which simultaneously satisfy multiple conflicting objectives to be determined. They applied that method to optimize the thermal exergy. Wagar et al.[13] analyzed thermodynamically an ammonia–water based Rankine cycle for renewable-based power production such as solar, geothermal, biomass, oceanic-thermal, and nuclear as well as industrial waste heat. They developed a model to optimize the thermodynamic cycle for maximum power output. Schuster et al. [14] presented the results from a simulation of the ORC and the optimization potential of the process when using supercritical parameters. The optimization processes were conducted using various working fluids of under different thermal efficiency and usable percentage of heat.

Using water, RC may generate useful power.However the thermodynamic thermal efficiency of Rankine cycle (TE) can still be optimized if modified cycles are utilized. To achieve this, RC should be considered in terms of its performance. Badr et al. [15] proposed an interactive (Basic language) computer programs for estimating the thermodynamic properties of water and steam, and for predicting the behaviors of simple, reheat and regenerative RC systems. The performances of RC power-systems, using steam as the working fluid, have been simulated and analyzed. Leeet. al [16] develop an analytical formula for estimating the Rankine power cycle efficiency at maximum power. Their results indicate that the thermal efficiency at maximum power depends primarily on the initial temperatures of the heating and cooling fluids and pinch-temperature differences between the working fluid and the heating and cooling fluids.

RC with reheating and regeneration stagesmay increase the average high temperature which in turn may improve the thermodynamic efficiency (TE). Habib et al. [17] presented a first- and second-law procedure for the optimization of the reheat pressure level in reheatregeneration thermal-power plants. Their procedure was applied for a thermal-power plant having two reheat pressure levels and two open-type feed-water heaters. They evaluated and optimized the second-law efficiency of the steam generator, turbine cycle and plant. A fraction of the steam is extracted at the exit of each turbinestage for regeneration.

The actual power cycle has limitation due to heat exchanging and cooling time and or space. Considering finite resource constraints, Bandyopadhyay et al. [18] studied thermo-economic optimization of a combined cycle power plant, comprised of an arbitrary number of internally irreversible Carnot-like heat engines.

The effect of bleeding pressure was investigated. van der Leeet al. [19] considered two calculation routines namely Quasi-Newton and a Derivative Free optimization for implementation in Cycle-Tempo(a general computer program for the analysis and optimization of energy systems). The energy system has closed feed-water heaters and steam bleed. The thermal efficiency was considered in relation to bleed pressure.

This study considers and focuses on the quantitative TEfor different RCs layouts under reheating and / or regenerative operations. The RCs are assumed ideal such that there are no pressure losses. The boiler and condenser efficiencies are not investigated. Therefore, infinite areas of heat exchangers are assumed.TE is the objective function with the constraints of non-saturated steam state at turbine(s) exits.

RC MODELS

Basic RC

RC consists of four processes as shown in Figure 1.

(a) 1 to 2: Isentropic compression by pump.
(b) 2 to 5: Isobaric heat supply by boiler.
(c) 5 to 6 Isentropic expansion by steam turbine and
(d) 6 to 1: Isobaric heat rejection by condenser.

The corresponding T-s diagram is clearly shown where all cycle stages are demonstrated by numbers from 1 to 7.

The output mechanical power of steam turbine, W_T,

$$W_T = \dot{m}\ (h_5\text{-}h_6) \tag{1}$$

The input mechanical power consumed by pump, W_P,

$$W_P = \dot{m}\ (h_2\text{-}h_1) \tag{2}$$

where $\dot{m}$ is the mass flow of the cycle.

Heat supplied from boiler,Q_B, is

$$Q_B = \dot{m}\ (h_5\text{-}h_2) \tag{3}$$

and the heat energy rejected by condenser, Q_C, is

$$Q_C = \dot{m}\ (h_6\text{-}h_1) \tag{4}$$

The net power output of RC,W, is

$$W = W_T - W_P \tag{5}$$

The TE,η, of RC is therefore

$$\eta = W/Q_B \tag{6}$$

or

$$\eta = \frac{\dot{m}((h_5 - h_6) - (h_2 - h_1))}{\dot{m}(h_5 - h_2)} \tag{7}$$

Eq. 7 can be simplified to become

$$\eta = \frac{(h_5 - h_6) - (h_2 - h_1)}{(h_5 - h_2)} \tag{8}$$

RC with Reheating

RC with reheating stages consists of at least five processes as shown in Figure 2 and 3.RC with one-reheating stage consists of five processes as shown in Figure 2. When compared with Figure 1, one process is added as reheating stage 6 to 7. Accordingly, there are two high boiler pressures, namely, $P_{2\text{-}5}$ and $P_{6\text{-}7}$. As reheating process (6 to 7) uses the same boiler, the exits temperatures, T_5 and T_7 are assumed equal. Thus

$$T_5 = T_7 \tag{9}$$

Similarly, a two-reheating stages RC (see Fig. 3) has

$$T_5 = T_7 = T_9 \tag{10}$$

The TE of RC with one stage-reheating, η_{1h},

$$\eta_{1h} = \frac{(h_5 - h_6) + (h_7 - h_8) - (h_2 - h_1)}{(h_5 - h_2) + (h_7 - h_6)} \tag{11}$$

The TE of RC with tworeheating-stages, η_{2h}, (see Fig. 3)

$$\eta_{2h} = \frac{(h_5 - h_6) + (h_7 - h_8) + (h_9 - h_{10}) - (h_2 - h_1)}{(h_5 - h_2) + (h_7 - h_6) + (h_9 - h_8)} \tag{12}$$

RC with Regeneration

RC with one-regeneration stage (see Fig. 4) consists of

(a) Two heating processes 9 to 12 and 5 to 6.
(b) One open feed heat exchanger and
(c) Two high working pressures $P_{9\text{-}12}$and $P_{3\text{-}6}$

The outlet-superheated steam at 12 to 5 is totally mixed with inlet-compressed water at 2 to 5. The heat rejected from upper cycle through 5 to 9 will be used to heat the compressed liquid of lower cycle from 2 to 5 such that

$$\dot{m}_a(h_5 - h_9) = \dot{m}_b\ (h_5 - h_2) \tag{13}$$

where $\dot{m}_a$ is the mass flow rate of upper cycle whereas $\dot{m}_b$ is the mass flow rate of lower cycle.

As

$$(h_5 - h_2)/\ (h_5 - h_9) > 1 \tag{14}$$

$$\dot{m}_b\ /\ \dot{m}_a < 1 \tag{15}$$

Since the two cycles share the same boiler

$$T_{12} = T_6 \tag{16}$$

The TE of RC with one stage regeneration, η_{1g},

$$\eta_{1g} = \frac{\dot{m}_a(h_{12}-h_5)-\dot{m}_a(h_9-h_3)+\dot{m}_b(h_6-h_7)-\dot{m}_b(h_2-h_1)}{\dot{m}_a(h_{12}-h_9)+\dot{m}_b(h_6-h_5)} \quad (17)$$

RC with one Reheating and one Regeneration Stage

RC with one- reheating and one-generation stage consists of (see Fig. 5)

(a) Four heating processes 11 to 14, 15 to 16, 5 to 6 and 7 to 8.
(b) One open feed heat exchanger and
(c) Four high working pressures P_{11-14}, P_{15-16}, P_{5-6} and P_{7-8}

Similar to Eqs 9 and 10,

$$T_{14} = T_{16} = T_6 = T_8 \quad (18)$$

The TE of RC with one-reheating and one-regeneration stage, η_{1h1g},

$$\eta_{1h1g} = \frac{\dot{m}_a((h_{14}-h_{15})+(h_{16}-h_5)-(h_{11}-h_3))+\dot{m}_b((h_6-h_7)+(h_8-h_9)-(h_2-h_1))}{\dot{m}_a((h_{14}-h_{11})+(h_{16}-h_{15}))+\dot{m}_b((h_6-h_5)+(h_8-h_7))} \quad (19)$$

RESULTS

Basic RC

The performance of basic RC (refer to Fig. 1) is considered under variable boiler pressure (P_{2-5}). The minimum boiler pressure is 20 bar while the maximum one is 200 bar. The condenser pressure is selected arbitrary to be 0.7 bar which corresponds to a saturation temperature of 89 ^{o}C. The maximum temperature of all power cycles is 999 ^{o}C. Figure 6 illustrates the influence of above variables on the TE,η. The results indicate that a higher boiler pressure results in a higher TE. The change of TE, η, is more noticeable at low boiler pressures. RC with a fixed maximum turbine's inlet temperature of 999 ^{o}C yields a higher TE if boiler pressure iskept the same. This is anticipated as a higher average boiler temperature, $\bar{T}_h$, is reached. At a boiler pressure of 20 bar, $\bar{T}_h$ =228^{o}C and 304^{o}C for RC with saturated outlet steam and with superheated one respectively. At boiler pressure of 200 bars, $\bar{T}_h$ =390^{o}C which in turn leads to a higher TE of 45.3%.The performance of RC may be investigated by considering the conditions needed for constant efficiencies as illustrated by Figure 7. It is found that for a giveniso-thermal efficiency the boiler pressure is inversely proportional to turbine inlet temperature and vice versa. Therefore, to increase the thermal efficiency both the boiler pressure and exit temperature should be increased.

RC with Reheating

An increase of average temperature, $\bar{T}_h$, can be achieved by reheating processes(refer to Figs 2 and 3). Figure 8 shows the performance of RC with one-reheating operation. A number of boiler outlet temperatures were considered. It is found that for a given outlet boiler temperature TE, η_{1h}, is increasing as intermediate boiler pressure, P_{6-7}, increases until a limit after which TE starts to decrease. The maximum (optimal) TE, η_{1h}, is increasing as boiler outlet temperature increases. It should be noticed that the optimal TE is linearly proportional to boiler pressure. When compared with basic RC, RC with one reheating stage has a higher TE if the same outlet boiler temperature is maintained but at the cost of a adding a reheating cycle. At boiler temperature of 999^{o}C an optimal TE of 47.64% is achieved which is larger than that of basic RC(i.e.45.27%). Therefore RC, with more reheating stages, may result in a higher thermal efficiency as shown in Figure 9. Here (refer to Fig. 3) there are two intermediate boiler pressures (i.e. $P_{6-7}$and P_{8-9}). For a given low boiler pressure, P_{8-9}, there exists an optimal high boiler pressure, P_{6-7} at which TE, η_{2h}, becomes maximum. P_{6-7} = 89.7 bar and P_{8-9}= 37.5 bar yield an optimal TE, η_{2h}, of 48.28%. This is slightly more than that of one-reheating stage RC (i.e. η_{1h}).The optimization of RC with multi-reheat stages includes more boiler pressure variables. Added to this, the optimal conditions might be associated with local maxima. The results of TE with more reheating stages had been extrapolated by using a rational function as indicated by Figure 10. The optimal (extrapolated) TE is slightly increased with the number of reheating stages. At large number of reheating stages the extrapolated TE value tends to 50.3%.

RC with Regeneration

Refer to Figure 4 which illustrates the regeneration operation of RC. The outlet-superheated steam at 12-5 is mixed with the compressed liquid (2 to 5) within the open feed heater. This will cool down the superheated steam from 5 to 9 and therefore increases the compressed water temperature from 2 to 5. Slight heat energy is added to bring the superheated steam at 5 to 6. Referring to Eqs. 13, 14 and 15, the mass flow rate of upper cycle, $\dot{m}_a$, (i.e. 3-9-10-11-12-5-4-3) is slightly larger than that of lower cycle, $\dot{m}_b$, (i.e. 1-2-3-4-5-6-7-8-1). The one-regenerative stage RC has similar features to that of one-reheating one but with different mass flow rates. RC with one-regeneration stage has two mass flow rates. As the mass flow rate of upper cycle is larger than that of lower one, the thermal efficiency is expected to increase. Figure 11 shows the variation of TE, η_{1g}, with low boiler pressure $P_{2\text{-}6}$. It is clearly demonstrated that there exists an optimal TE, η_{1g}, for a given maximum boiler temperature. The optimal TE, η_{1g}, increases as the maximum temperature increases. The maximum TE, η_{1g}, for one-regenerative stage RC is 49%, which is larger than that of RC with one-reheating stage (i.e. 47.6%). The TE global optimization process of multi-stages regenerative RC is cumbersome therefore random intermediate boiler pressures were considered to achieve near optimal TE (see Fig 12). This is performed for a maximum of four regenerative stages RCs. To estimate the maximum optimal TE an extrapolated rational function is curve-fitted. The maximum optimal (extrapolated) TE is about 51%, which is slightly larger than that of RC with multi-reheat stages (i.e. 50.3%).

RC with Reheating and Regeneration

Both reheating and regeneration may improve TE therefore RC with one-reheating and one- regenerative stages (refer to Fig. 5) is considered. This is a combined process where intermediate reheating stage is imposed for the upper (3-11-12-13-14-15-16-5-4-3) and lower (1-2-3-4-5-6-7-8-9-10-1) cycles. Two cases of interests are analyzed: (1) equal pressure drops across turbines (Fig. 13) and (2) non-equal pressure dropswith optimization (Fig. 14). The first case yields TE= 50.2 whereas the second one has near-optimal TE=50.9%. RC with three reheating stages (refer to Fig. 10) yields TE=49%. Therefore, regeneration processes can always improve TE for RC with reheating stages.

CONCLUSIONS

Threevariations of Rankine cycle were analyzed under given constraints.

It is found that:

(1) The basic RC with low boiler pressure may have a higher TE if the turbine exit steam is superheated.
(2) The TE of regenerative RC is higher than that of reheated one if the same number of intermediate boiler pressures is kept the same.
(3) Increasing the number of regeneration and/or reheating stages enlarge TE of RC.
(4) The maximum TE may be achieved if the highest inlet-to-turbine temperature applies.

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LIST OF FIGURES

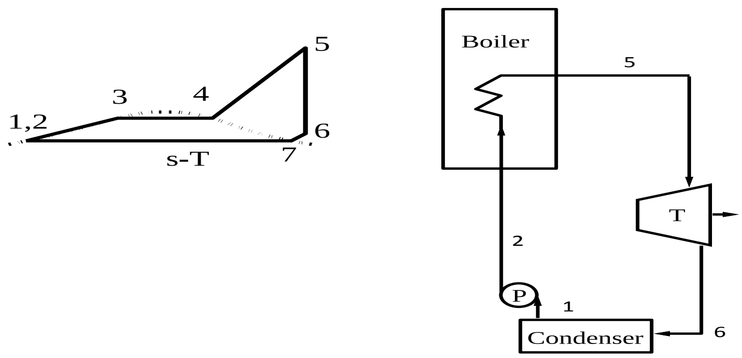

Figure 1: Basic RC

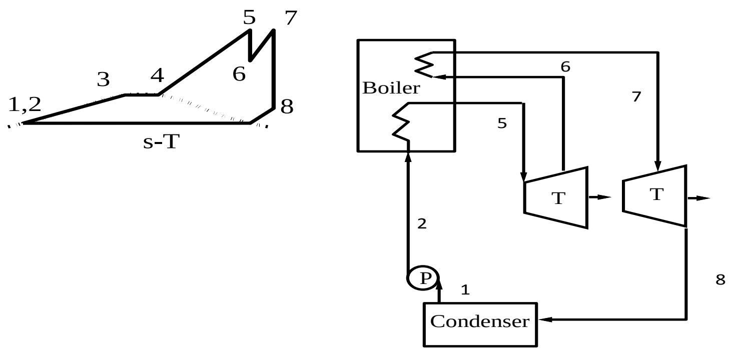

Figure 2: RC with one- Reheating Stage

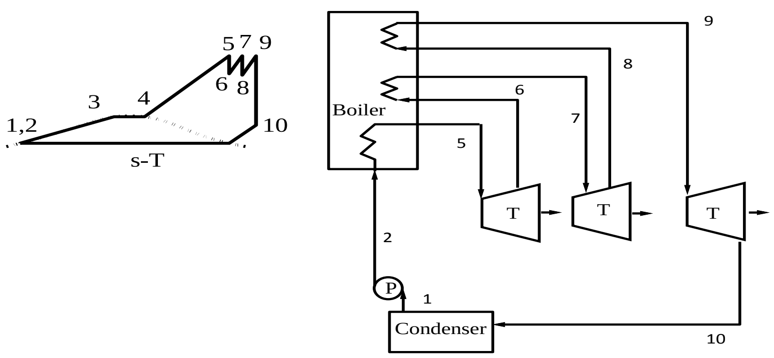

Figure 3: RC with two- Reheating Stages

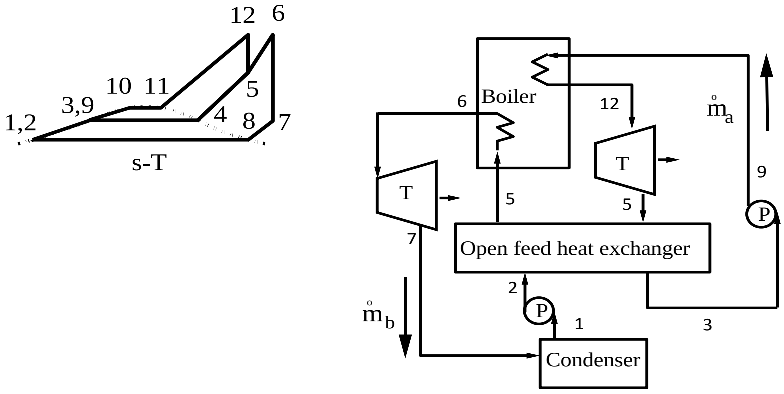

Figure 4 RC with one- Regenerative Stage

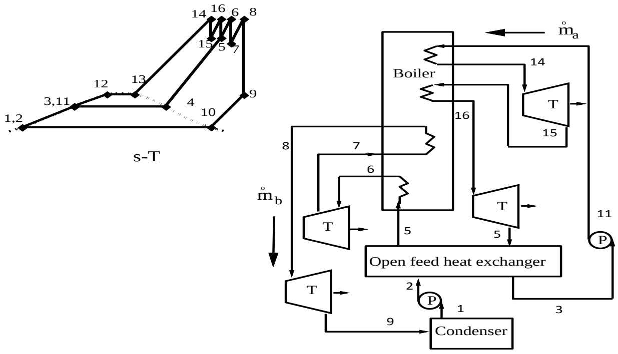

Figure 5 RC with one- Regenerative-one-Reheating Stage

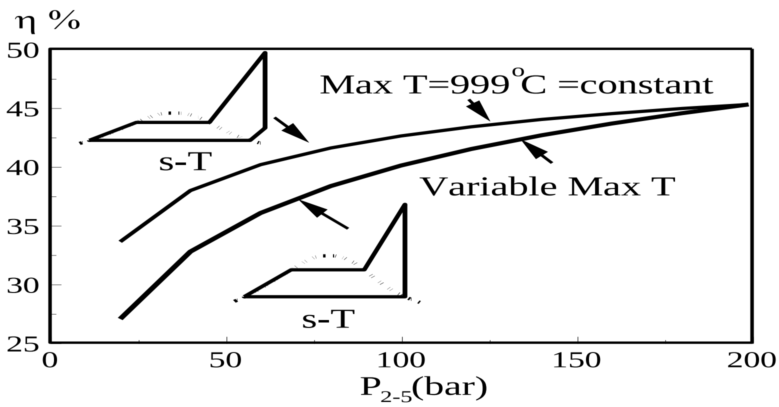

Figure 6: Effect of Boiler Pressure, P_{2-5}, and Superheated Steam Temperature on TE of Basic RC

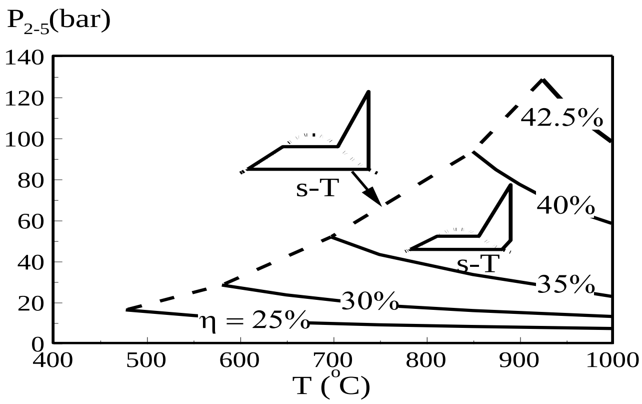

Figure 7: Iso-TE of Basic RC

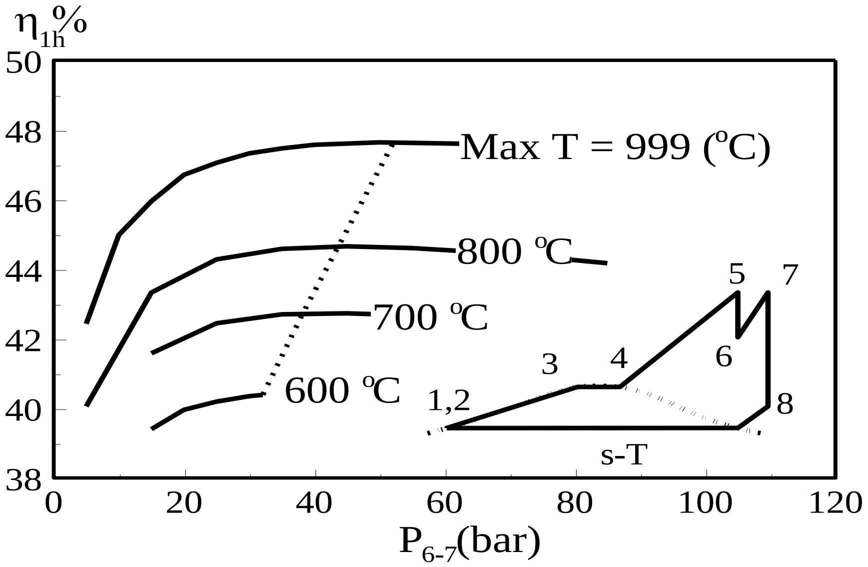

Figure 8: Effect of Intermediate Boiler Pressure, $P_{6\text{-}7}$, and the Maximum Cycle Temperature on TE of one-Reheating Stage RC

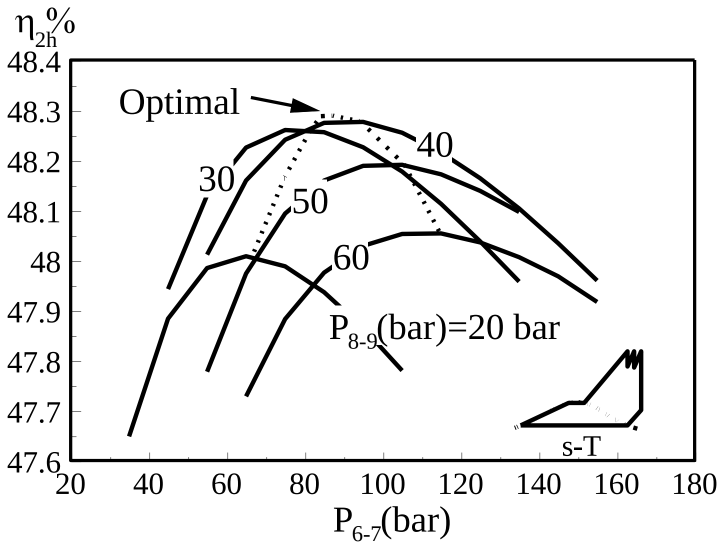

Figure 9: Effect of Intermediate Boiler Pressures, $P_{8\text{-}9}$ and $P_{6\text{-}7}$, on TE of two-Reheating Stages RC

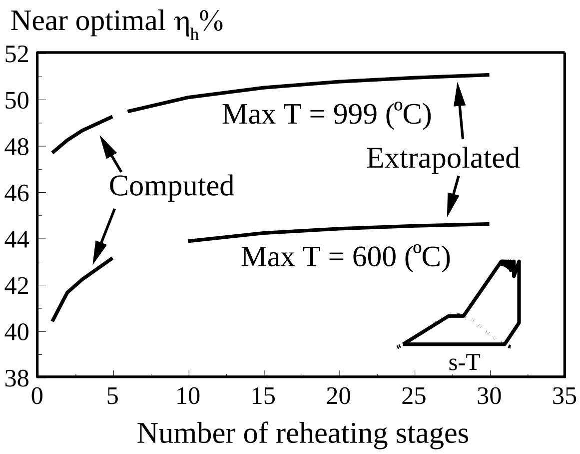

Figure 10: Effect of Number of Reheating Stages on TE of RC

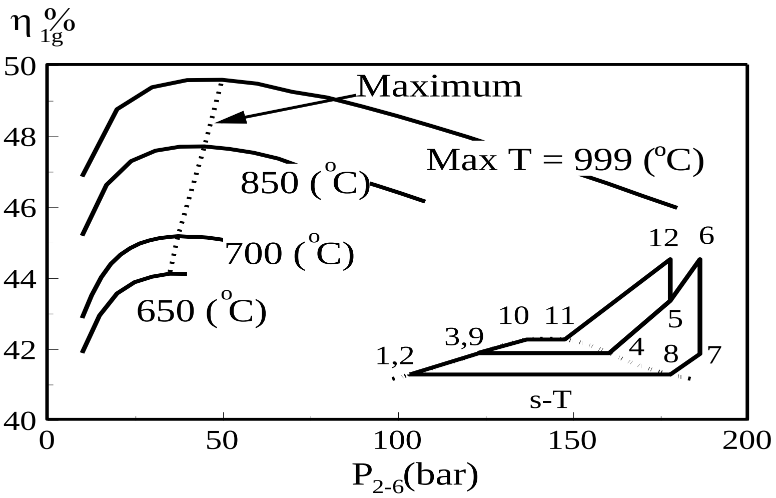

Figure 11: Effect of Intermediate Boiler Pressure, $P_{2\text{-}6}$, on TE of one-Regenerative Stage RC

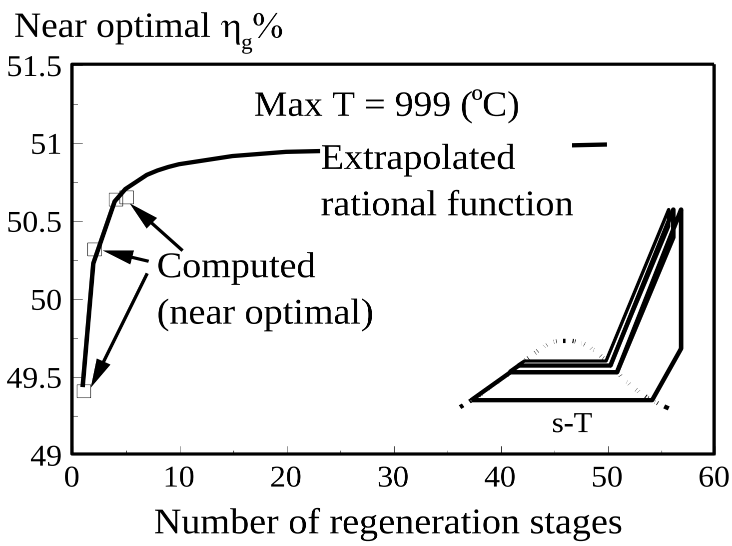

Figure 12: Effect of Number of Regenerative Stages on TE of RC

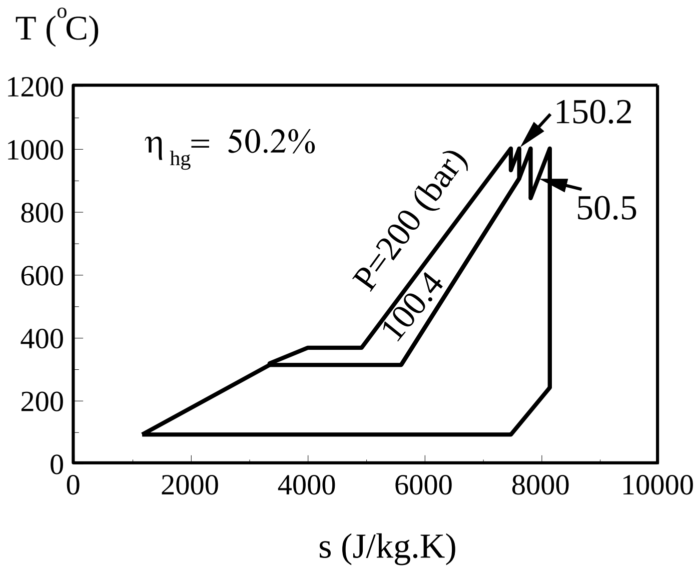

Figure 13: Thermal Performance of one-Reheating-one-Regenerative Stage RC with Equal Pressure Drops

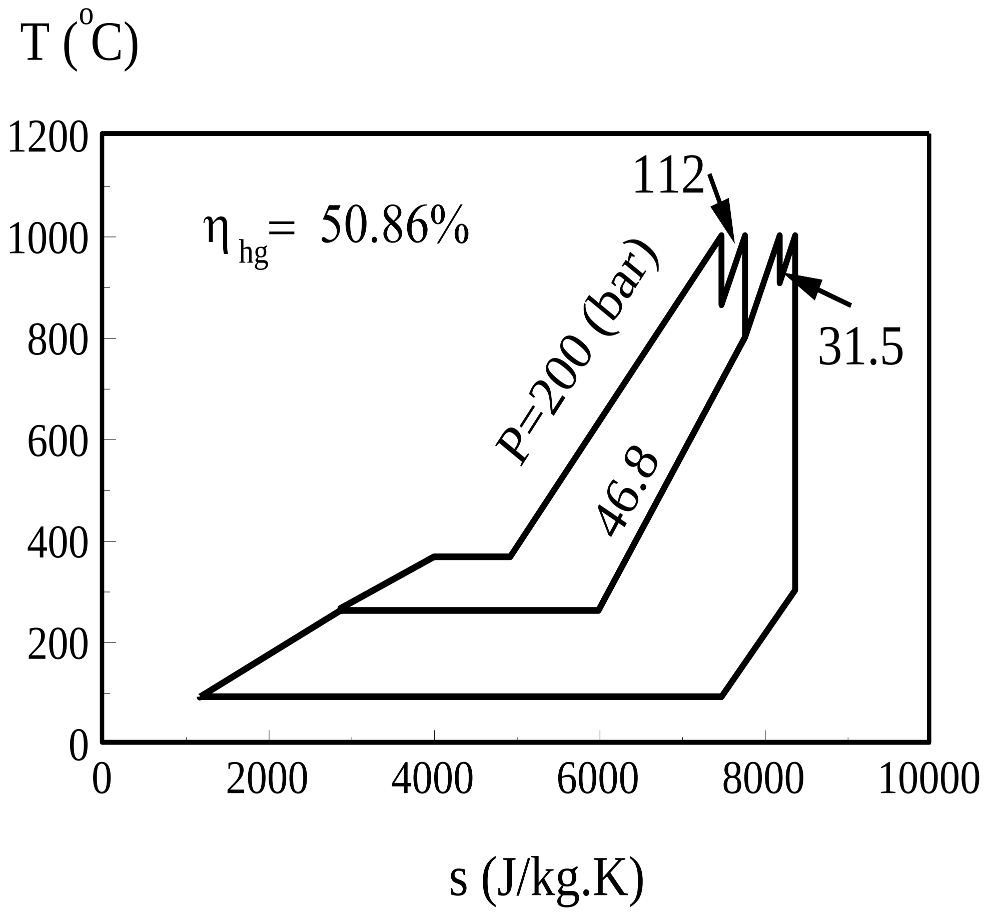

Figure 14 Thermal Performance of one-Reheating-one-Regenerative Stage RC with Non-Equal Pressure Drops