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Second law analysis of a waste heat recovery based power generation system

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Abstract

In the present paper the performance of a waste heat recovery power generation system based on second law analysis is investigated for various operating conditions. The temperature profiles across the heat recovery steam generator (HRSG), network output, second law efficiency and entropy generation number are simulated for various operating conditions. The variation in specific heat with exhaust gas composition and temperature are accounted in the analysis and results. The effect of pinch point on the performance of HRSG and on entropy generation rate and second law efficiency are also investigated. The second law efficiency of the HRSG and power generation system decreases with increasing pinch point. The first and second law efficiency of the power generation system varies with exhaust gas composition and with oxygen content in the gas. Approximating the exhaust gas as air, and the air standard analysis leads to either underestimation or overestimation of power plant performance on both first law and second law point of view. Actual gas composition and specific heat should be used to accurately predict the second law performance. The present results contribute further information on the role of gas composition, specific heat and pinch point influence on the performance of a waste heat recovery based power generation system based on first and second law of thermodynamics.

Keywords: Heat recovery steam generator; Waste heat recovery; Second law efficiency; Pinch point; Gas composition; Performance

1. Introduction

The rising cost of energy and the global warming in recent years have highlighted the need to develop advanced energy systems to increase efficiency and to reduce emissions. The availability of energy plays an important role in the development and prosperity of a nation [1]. In recent years, waste heat recovery, renewable energy sources, cogeneration and combined cycle power generation systems are receiving a great deal of attention [2]. There is a great scope to recover waste heat from various industries and to generate power or process heat using a heat recovery steam generator (HRSG). Also the HRSG is used in a gas turbine and steam turbine based power plant to recover waste heat from gas turbine exhaust gas and to generate steam. From an economic standpoint, HRSG performance is very important to the operation of these advanced energy systems as each additional unit of steam generated represents additional power generation or process heat for application [3].

There is published literature based on first law of thermodynamics on the effect of pinch point on waste heat recovery based power generation or cogeneration systems. First law analysis does not account for the irreversibility or degradation of energy in the system. Second law analysis provides an effective technique for measuring and optimizing performance of a thermal system by accounting for the energy quality. Second law analysis of thermal systems is widely gaining acceptance over traditional energy methods in both industry and academia as it is developed into a set of standards for measuring the performance [4]. First law

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Nomenclature

c_p	specific heat (kJ kg^{-1} K^{-1})
$\dot{E}$	energy transfer rate (kW)
h	specific enthalpy (kJ kg^{-1})
hl	factor which accounts heat losses
HRSG	heat recovery steam generator
$\dot{m}$	mass flow rate (kg s^{-1})
M	molar mass (kg kmol^{-1})
Ns	entropy generation number
P	pressure (bar)
PP	pinch point (K)
$\dot{Q}$	rate of heat transfer (kW)
R	universal gas constant (kJ kmol^{-1} K^{-1})
$\dot{S}_{gen}$	entropy generation rate (kW kg^{-1} K^{-1})
s	specific entropy (kJ kg^{-1} K^{-1})
T	temperature (K)
$\dot{W}$	rate of work output (MW)
x	steam or water quality
y	mass fraction of gas

Symbols

$\Delta P/P$	pressure drop (%)
$\dot{\Xi}$	exergy transfer rate (MW)
η	first law efficiency
η_t	turbine isentropic efficiency
η_p	pump isentropic efficiency
φ	second law efficiency

Subscripts

econ	economizer
evap	evaporator
f	fluid
g	gas
o	environment
p	pump
s	steam
sat	saturated
super	superheater
system	waste heat power generation system
t	turbine
w	water

analysis provides information into how efficiently energy is converted while exergy analysis represents energy "quality" [5]. Unlike energy, exergy is destroyed by irreversibilities (entropy generation) such as friction, heat loss or chemical irreversibilities [5]. For this reason, second law analysis provides a true measure of HRSG and waste heat recovery power generation system performance.

Valdes et al. [6] have proposed a thermoeconomic model for selecting the design point for HRSGs in a combined cycle setting that accounts for both the cost of energy and annual cash flows. Ong'iro et al. [7] performed a numerical simulation of a commercial HRSG in a combined cycle arrangement to account for design and operational constraints under full and part-load conditions, while Valdes and Rapun [8] have used influence coefficients to optimize HRSG design. Karthikeyan et al. [9] investigated the effect of supplementary firing on HRSG performance in a cogeneration configuration. Cenusa et al. [10] analyzed HRSG performance based on both performance and the capital cost of heat transfer area. Nag and De [2] conducted second law analysis for a HRSG producing saturated steam, while Reddy et al. [11] conducted second law analysis for a waste heat recovery steam generator producing superheated steam. Karthikeyan et al. [9] have reported some preliminary trends regarding steam generation and work output for an industrial waste heat recovery based cogeneration system.

In the published literature, not much is reported on the effect of exhaust gas composition, the variation of specific heat with gas composition and gas inlet temperature, pinch point and other operating parameters on entropy generation rate and second law efficiency for a heat recovery steam generator (HRSG) and for a waste heat recovery based power generation system. The objective of the present work is to investigate the performance of a HRSG and waste heat recovery based power generation system using the second law of thermodynamics for various operating conditions such as gas composition, specific heat, pinch point and gas inlet temperature. This will contribute some original information on the role of operating variables and will be useful in the design of HRSG and waste heat recovery based power generation systems.

2. Formulation of the problem

In the present work, a waste heat recovery based steam generator (HRSG) with an economizer, evaporator and superheater is considered. The steam generated in HRSG is then expanded in a steam turbine for power generation. A schematic representation of the waste heat recovery power generation system with the details is shown in Fig. 1.

The typical temperature profiles of the gas and water/steam in the HRSG are shown in Fig. 2. The hot exhaust gas enters the superheater at T_{g1} and flows through the evaporator and economizer to T_{g4} where the gas is discharged to the environment. Water enters the economizer at temperature T_{w1} and is sensibly heated to T_{w2} and enters into the evaporator. The water boils in the evaporator (saturation temperature T_s) and enters the superheater as a sat-

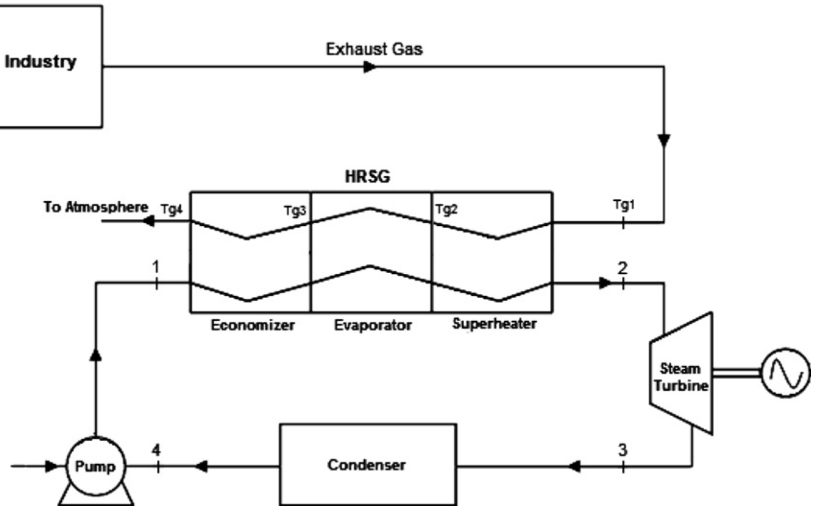

Fig. 1. Waste heat recovery based power generation system concept [9].

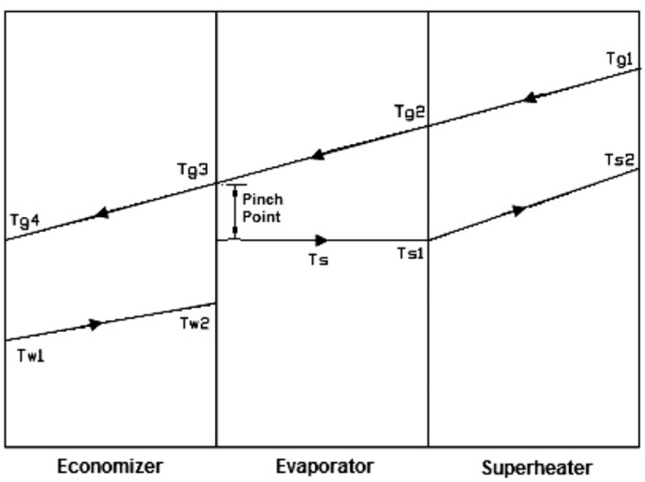

Fig. 2. Typical temperature profiles for a single-pressure HRSG.

urated steam, where it is superheated from T_{s1} to T_{s2}. The superheated steam is then delivered to a steam turbine.

The following assumptions are made in the analysis [2]:

- System is at steady state.
- No pressure drop on steam side.
- Pressure drop on gas side does not affect its temperature.
- Approach point is negligible.

2.1. Thermodynamic analysis

Using the temperature profiles and pinch point, the gas temperature entering the economizer in HRSG is written as (Fig. 2)

$$T_{g3} = T_{sat} + PP \tag{1}$$

where T_{sat} is the saturation temperature at the considered pressure and PP is pinch point.

The steam generation rate in the HRSG is determined by taking a control volume of the superheater and evaporator and by performing the energy balance.

$$\dot{m}_s = \frac{\dot{m}_g(c_{pTg1}T_{g1} - c_{pTg3}T_{g3})(1 - hl)}{(h_{s2} - h_{w2})} \tag{2}$$

where $\dot{m}_g$ is the mass flow rate of gas, c_p is the specific heat of the gas, hl is the percentage of heat lost in the HRSG (typically 2–3%) and h_{s2} and h_{w2} are the enthalpies of the steam at the superheater outlet and water at evaporator inlet, respectively.

The gas temperature leaving the superheater is determined from a control volume and energy balance of the superheater. Solving for T_{g2} and assuming $c_{pTg2} = c_{pTg1}$

$$T_{g2} = \frac{c_{pTg1}T_{g1}}{c_{pTg2}} - \frac{\dot{m}_s(h_{s2} - h_{s1})}{\dot{m}_g c_{pTg2}(1 - hl)} \tag{3}$$

Now the specific heat at T_{g2} is determined and is used to recalculate T_{g2} using Eq. (3). The recalculated T_{g2} is used in the further analysis and calculations.

The gas outlet temperature at the economizer T_{g4} is determined in a similar manner to T_{g2}.

A control volume and energy balance of the economizer yields

$$T_{g4} = \frac{c_{pTg3}T_{g3}}{c_{pTg4}} - \frac{\dot{m}_s(h_{w2} - h_{w1})}{\dot{m}_g c_{pTg4}(1 - hl)} \tag{4}$$

2.2. Thermodynamic properties of an ideal gas mixture

The exhaust gas is considered as an air in one test case and the actual gas composition in other cases. The specific heat of air is calculated using standard thermodynamic tables. The specific heat of the actual exhaust gas is determined using the relation from Moran and Shapiro [12].

$$c_p = \frac{R}{M}(\alpha + \beta T + \gamma T^2 + \delta T^3 + \varepsilon T^4) \quad (5)$$
T is in K, equation valid from 300–1000 K

where R is the universal gas constant, M is the molar mass of the gas, and α, γ, δ and ε are gas constants for various ideal gases.

The specific heat of a mixture of gasses is expressed as the sum of the specific heats of each component and their mass fraction y_i

$$c_p(T) = \sum_{i=1}^{n} y_i c_{p_i}(T) \quad (6)$$

The entropy change for an ideal gas mixture is expressed as

$$s_2 - s_1 = \sum_{i=1}^{n} y_i (s_2 - s_1)_i \quad (7)$$

2.3. Network output

The network output for the power generation system is

$$\dot{W}_{\text{net}} = \dot{W}_t - \dot{W}_p \quad (8)$$

First law efficiency

The first law efficiency of the waste heat power generation system is defined as the ratio of the network output to heat input. This parameter provides a measure of how efficiently the energy input is converted to useful work output. The first law efficiency for the waste heat recovery power generation system is expressed as

$$\eta_{\text{system}} = \frac{\dot{W}_{\text{net}}}{\dot{Q}_{\text{input}}} = \frac{\dot{W}_{\text{net}}}{\dot{m}_{\text{g}} c_{p\text{Tg1}} T_{\text{g1}}} \quad (9)$$

2.4. Entropy generation number of HRSG

The entropy generation number is a dimensionless parameter used to relate the total entropy generation rate in a system and is defined as

$$N_{\text{s}} = \frac{\dot{S}_{\text{gen}}}{\dot{m}_{\text{g}} c_{p1-4}} \quad (10)$$

where c_{p1-4} is the average specific heat of the gas across the HRSG.

The entropy generation rates for the gas and water/steam in the HRSG are

$$\dot{S}_{\text{gas}} = \dot{m}_{\text{g}}(s_{\text{g4}} - s_{\text{g1}}) \quad (11\text{a})$$

$$\dot{S}_{\text{steam}} = \dot{m}_{\text{s}}(s_{\text{s2}} - s_{\text{w1}}) \quad (11\text{b})$$

where the entropy for the gas and water/steam are evaluated at the corresponding states.

As external heat loss is included in the model, entropy generation due to heat transfer to the surroundings is also accounted.

The entropy generation rate due to heat loss in the HRSG is expressed as

$$\dot{S}_{\text{hl}} = \frac{\dot{m}_{\text{g}}(c_{p\text{Tg4}} T_{\text{g4}} - c_{p\text{Tg1}} T_{\text{g1}})\text{hl}}{(T_{\text{g4}} + T_{\text{g1}})/2} \quad (12)$$

The entropy generation number for the HRSG is expressed as

$$Ns = \frac{\dot{S}_{\text{gas}} + \dot{S}_{\text{steam}} + \dot{S}_{\text{hl}}}{\dot{m}_{\text{g}} c_{p1-4}} \quad (13)$$

2.5. Second law efficiency

The first law efficiency is a measure of the amount of energy transferred between the gas and steam while second law efficiency represents how effectively the energy is transferred or the quality. Second law analysis makes it possible to compare many different interactions in a system, and to identify the major sources of exergy destructions/losses [5].

HRSG

Heat transfer to water/steam in the HRSG is written as

$$\dot{Q} = \dot{m}_{\text{s}}(h_{\text{s2}} - h_{\text{w1}}) \quad (14)$$

The change in availability of the gas and steam is

$$\Delta\dot{\Xi}_{\text{gas}} = \dot{Q} - \dot{m}_{\text{g}} T_0 (s_{\text{g1}} - s_{\text{g4}}) \quad (15)$$

$$\Delta\dot{\Xi}_{\text{steam}} = \dot{Q} - \dot{m}_{\text{s}} T_0 (s_{\text{s2}} - s_{\text{w1}}) \quad (16)$$

The change in availability for heat transfer across a boundary of temperature T_{b} is defined as

$$\Delta\dot{\Xi}_{\text{hl}} = \dot{Q}_{\text{lost}}\left(1 - \frac{T_0}{T_{\text{b}}}\right) \quad (17)$$

The change in availability due to heat loss in the HRSG is

$$\Delta\dot{\Xi}_{\text{hl}} = \dot{m}_{\text{g}}(c_{p\text{Tg1}} T_{\text{g1}} - c_{p\text{Tg4}} T_{\text{g4}})\text{hl}\left(1 - \frac{T_0}{(T_1 + T_4)/2}\right) \quad (18)$$

The second law efficiency of the HRSG is calculated as the ratio of the change in availability of the gas (cooling) to the change in availability of the water/steam (heating)

$$\Psi_{\text{HRSG}} = \frac{\Delta\dot{\Xi}_{\text{steam}}}{\Delta\dot{\Xi}_{\text{gas}} + \Delta\dot{\Xi}_{\text{hl}}} \quad (19)$$

Waste heat recovery power generation system

The availability of the exhaust gas entering the HRSG with reference to the environment is defined as

$$\Delta\dot{\Xi}_{\text{gas}} = \dot{m}_{\text{g}}[(h(T_{\text{g1}}) - h(T_0)) - T_0(s(T_{\text{g1}}) - s(T_0))] \quad (20)$$

where T_0 is the environment or ambient temperature and $s(T)$ is specific entropy.

The second law efficiency of the waste heat power generation system is defined as the ratio of network output to the availability of the gas.

$$\Psi_{\text{system}} = \frac{\dot{W}_{\text{net}}}{\Delta\dot{\Xi}_{\text{gas}}} \tag{21}$$

3. Results and discussion

The exhaust gas composition used and the operating details for the present analysis are listed in Tables 1 and 2, respectively. The gas composition is varied to provide insight on how gas composition influences specific heat and how specific heat affects performance of the HRSG and waste heat recovery power generation system based on both first law and second law point of view. The exhaust gas compositions are taken from Cihan et al. [13] and Moran and Shapiro [12] where the fuel burned is natural gas. The combustion products and mass fractions of each gas are shown in Table 1. The test parameters used in the simulation of the waste heat recovery power generation system are shown in Table 2.

3.1. Effect of pinch point on temperature profiles and on steam generation rate in HRSG

The effect of pinch point on water/steam and gas temperature profiles across HRSG is presented in Fig. 3. Higher pinch points result in increased gas temperature entering the economizer resulting in reduced heat transfer in the superheater and evaporator and ultimately resulting in lower steam generation rate. Lower steam generation leads to reduced heat transfer in the economizer and higher exit gas temperatures. Higher exit gas temperatures indicate lower waste heat recovery in the HRSG. The temperature details are generated for Gas I composition as described in Table 1. For better performance based on second law point of view, low pinch points are favorable. This also results in less irreversibilities in HRSG due to less temperature difference between gas and water/steam. The variation of steam generation rate in HRSG with pinch point is demonstrated in Fig. 4. Higher pinch points result in lower heat recovery in the heat recovery steam generator. Higher pinch point increases gas temperature in the evaporator and economizer.

Table 1
Exhaust gas composition [12,13]

Combustion products	Mass fraction (%)		
	Gas I	Gas II	Air
CO_2	4.42	10.28	–
H_2O	3.43	8.41	–
O_2	16.55	7.48	20.95
N_2	75.6	73.82	78.08
Ar	–	–	0.93
Other	–	–	0.01

Table 2
System test parameters

Test parameters	
Gas mass flow rate (kg/s)	100.00
Gas inlet temperature (K)	773.00
Saturation temperature (K)	549.73
Steam pressure (bar)	60.00
Steam outlet temperature (K)	623.00
Pinch point (K)	20.00
Heat loss (%)	2.00
Pressure loss (%)	5.00
Turbine isentropic efficiency (%)	85.00
Pump isentropic efficiency (%)	85.00
Condenser pressure (bar)	0.10
Environment temperature (K)	293.00

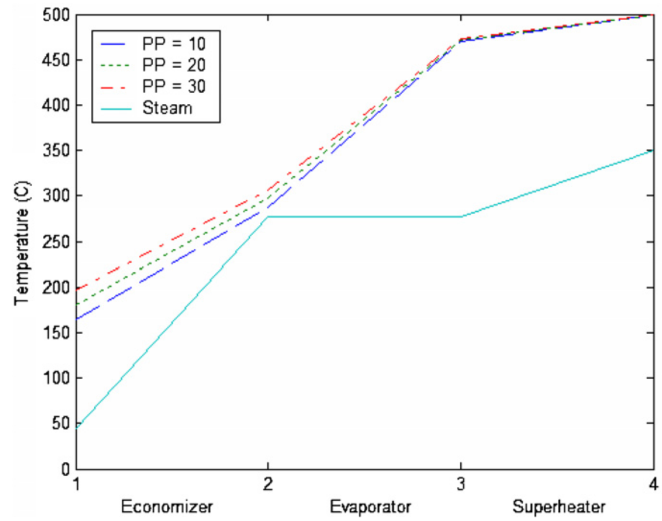

Fig. 3. Temperature profile variation with pinch point across HRSG; $\dot{m}_g = 100$ kg/s, $T_{g1} = 773$ K, $T_{s2} = 623$ K, $P = 60$ bar, Gas I: 4.42% CO_2, 16.55% O_2, 3.43% H_2O, 75.6% N_2.

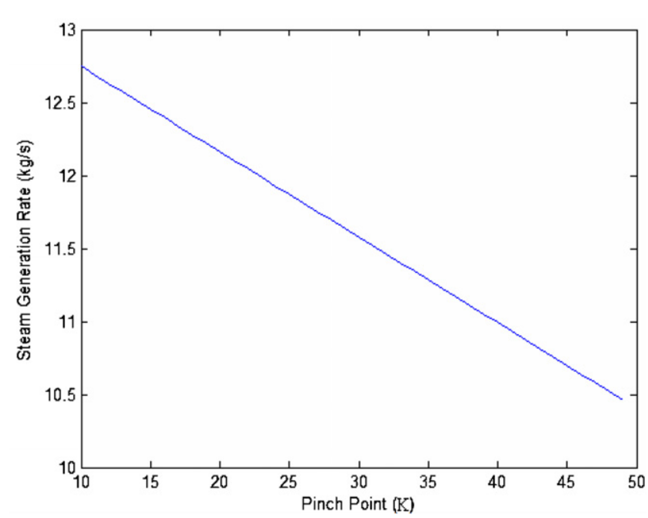

Fig. 4. Steam generation rate variation with pinch point in HRSG; $\dot{m}_g = 100$ kg/s, $T_{g1} = 773$ K, $T_{s2} = 623$ K, $P = 60$ bar, Gas I: 4.42% CO_2, 16.55% O_2, 3.43% H_2O, 75.6% N_2.

3.2. Effect of gas composition and inlet temperature on first law efficiency of the waste heat recovery power generation system

The variation of steam generation rate in HRSG with gas inlet temperature for a particular pinch point (20 K) is shown in Fig. 5. The steam generation rate increases with gas inlet temperature due to more energy input to the HRSG. For any gas inlet temperature and for a fixed pinch point, the steam generation rate varies with exhaust gas composition. This clearly demonstrates that the actual gas composition and the corresponding specific heat have influence on steam generation and should be considered for correct estimation of steam generate rate and the work outputs. Assuming the gas as an air and the calculations based on air standard approach will not provide correct steam generation rate in HRSG. The steam turbine network output variation with exhaust gas inlet temperature for a particular pinch point is presented in Fig. 6. The network output increases with gas inlet temperature as expected due to more steam generation rate in HRSG. However, the net work output for any gas inlet temperature depends on the exhaust gas composition. Treating the gas as an air and the calculations based on air standard analysis may provide reasonable values close to the real case, but always results in significant error or over/underestimation of the performance. The results clearly demonstrate that gas composition has significant influence on the performance of the system. The effect of gas composition on first law efficiency of the system is demonstrated in Fig. 7. The first law efficiency varies with gas composition and oxygen content in the gas. The specific heat varies with gas composition which influences heat transfer. The increased heat recovery translates into increased steam production, which increases work output for the same heat

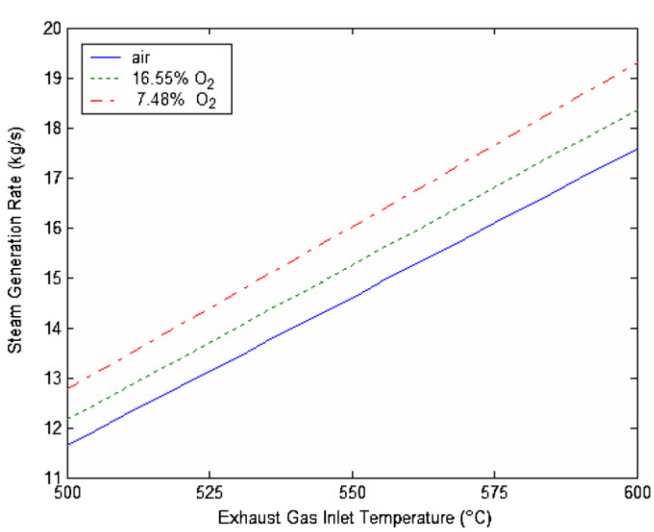

Fig. 5. Variation of steam generation rate in HRSG with gas composition and inlet temperature; $\dot{m}_g = 100$ kg/s, PP = 20 K, $T_{s2} = 623$ K, $P = 60$ bar, Gas I: 4.42% CO_2, 16.55% O_2, 3.43% H_2O, 75.6% N_2, Gas II: 7.48% O_2 (details are listed in Table 1).

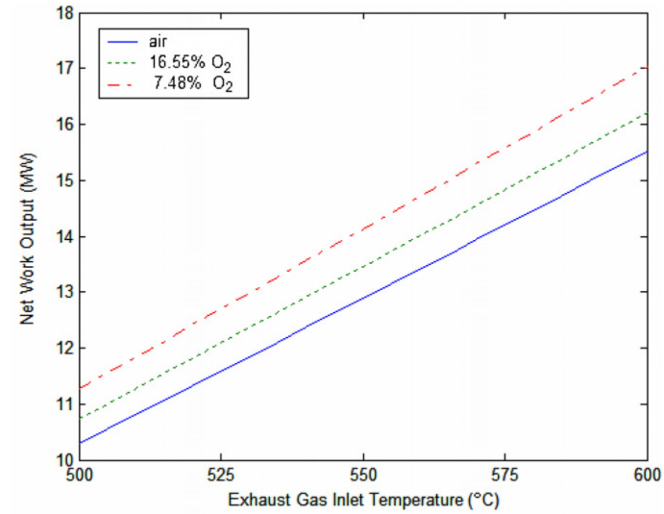

Fig. 6. Network output variation with gas composition and inlet temperature; $\dot{m}_g = 100$ kg/s, PP = 20 K, $T_{s2} = 623$ K, $P = 60$ bar, Gas I: 4.42% CO_2, 16.55% O_2, 3.43% H_2O, 75.6% N_2, $\eta_t = 85\%$, $\eta_p = 85\%$, Gas II: 7.48% O_2 (details are listed in Table 1).

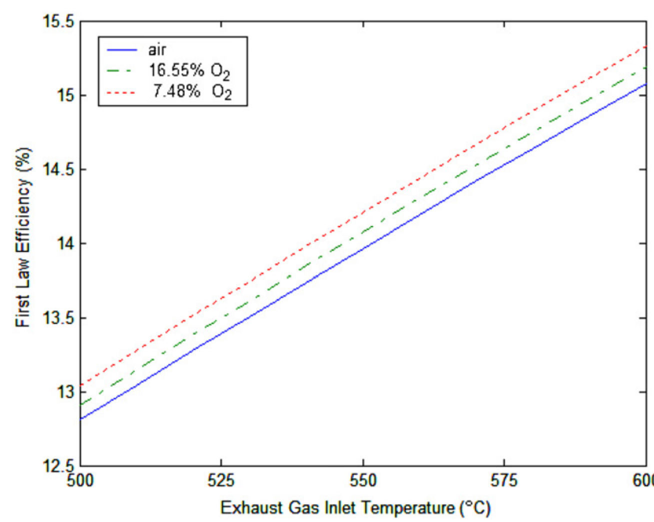

Fig. 7. First law efficiency variation of the waste heat power generation system with gas composition and inlet temperature; $\dot{m}_g = 100$ kg/s, $T_{g1} = 773$ K, $T_{s2} = 623$ K, $P = 60$ bar, PP = 20 K, Gas I: 4.42% CO_2, 16.55% O_2, 3.43% H_2O, 75.6% N_2, Gas II: 7.48% O_2 (details are listed in Table 1).

input. The analysis based on air standard approach underestimates first law efficiency and actual gas composition should be used to accurately predict first law performance.

3.3. Effect of gas composition and inlet temperature on second law efficiency and entropy generation number of the HRSG

The effect of gas composition on second law efficiency for the HRSG is shown in Fig. 8. For the same pinch point second law efficiency increases with exhaust gas inlet

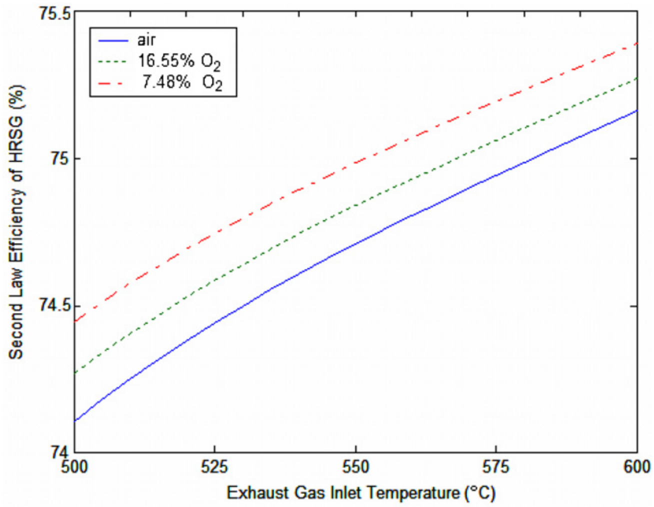

Fig. 8. Second law efficiency variation of HRSG with gas composition and inlet temperature; $\dot{m}_g = 100$ kg/s, $T_{g1} = 773$ K, $T_{s2} = 623$ K, $P = 60$ bar, PP = 20 K, Gas I: 4.42% CO_2, 16.55% O_2, 3.43% H_2O, 75.6% N_2, Gas II: 7.48% O_2 (details are listed in Table 1).

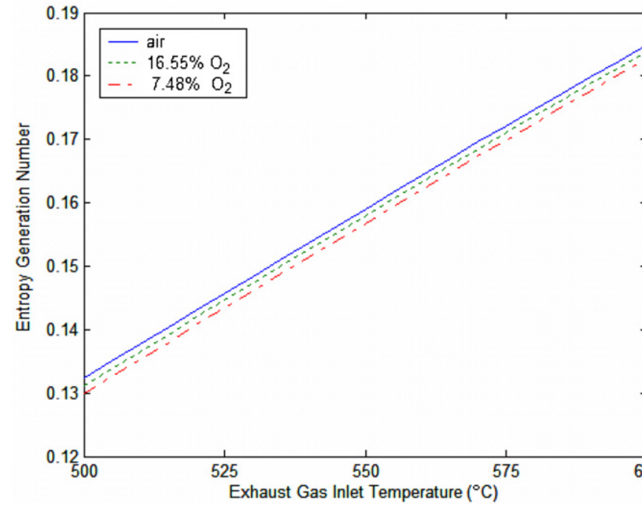

Fig. 9. Variation of HRSG entropy generation number with gas composition and inlet temperature; $\dot{m}_g = 100$ kg/s, $T_{g1} = 773$ K, $T_{s2} = 623$ K, $P = 60$ bar, PP = 20 K, Gas I: 4.42% CO_2, 16.55% O_2, 3.43% H_2O, 75.6% N_2, Gas II: 7.48% O_2 (details are listed in Table 1).

temperature. The second law efficiency depends on exhaust gas composition. The second law efficiency is underestimated using air standard analysis and the difference in second law performance between an actual gas and assuming it as air becomes more pronounced at low gas inlet temperatures. An actual gas mixture has a different specific heat than air and therefore the steam production rate is different in the HRSG. The actual consideration of exhaust gas composition and the associated enthalpy, entropy values resulting higher second law efficiency values than based on air standard analysis. The results clearly demonstrate that analysis of the waste heat power generation system based on the air standard approach will underestimate second law efficiency. It is always better to consider the actual gas composition and the corresponding values in the calculations and analysis. Also, the composition of the exhaust gas significantly affects the performance of the system as demonstrated by the second law efficiency variation with gas inlet temperature for two exhaust gas compositions (with different oxygen contents) as listed in Table 1.

The effect of gas composition and inlet temperature on entropy generation number for HRSG is presented in Fig. 9. For same pinch point the entropy generation number increases with gas inlet temperature due to increased irreversibilities in HRSG. The results demonstrate that the entropy of gas depends on gas composition and this reflects in entropy generation rate also. The specific heat of the gas depends on gas composition and it affects the performance both on first and second law point of view. This effect becomes more pronounced depending on oxygen content in the exhaust gas and exhaust gas composition. However, since the entropy generation number equation contains specific heat in the denominator, the specific heat has influence on entropy generation and on entropy generation number.

3.4. Effect of operating conditions on second law efficiency of the waste heat recovery power generation system

3.4.1. Gas composition and inlet temperature

The second law efficiency of the waste heat recovery power generation system increases with exhaust gas inlet temperature as shown in Fig. 10. Higher gas inlet temperatures increases steam generation rate in HRSG, network output and availability of the gas. The gas composition influences second law efficiency of the power generation system. For same pinch point, and gas inlet temperature the second efficiency is different for different gas compositions. This clearly demonstrates that treating gas as air

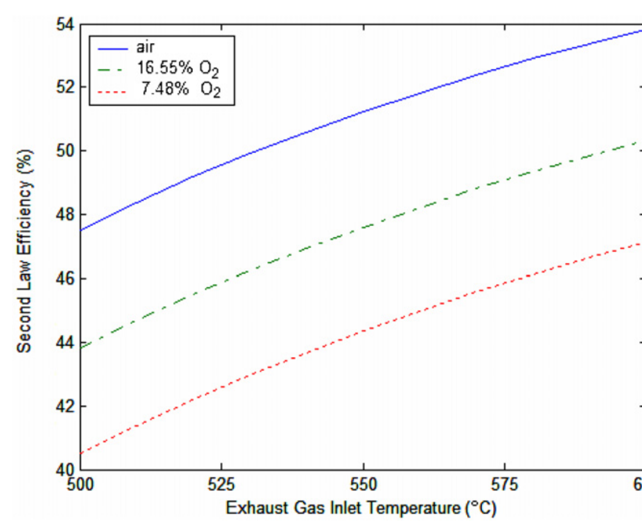

Fig. 10. Second law efficiency variation of waste heat power generation system with gas composition and inlet temperature; $\dot{m}_g = 100$ kg/s, PP = 20 K, $T_{s2} = 623$ K, $P = 60$ bar, Gas I: 4.42% CO_2, 16.55% O_2, 3.43% H_2O, 75.6% N_2, Gas II: 7.48% O_2 (details are listed in Table 1).

and doing the second law analysis based on air results in prediction of the power generation system performance on low or high side. Though the second law efficiency variation trends are same with gas inlet temperature, the gas composition has influence on heat recovery, temperature profiles in HRSG, irreversibilities in HRSG, first and second law efficiencies of power generation unit. Modeling the exhaust gas as an air can significantly overestimate the second law efficiency of waste heat power generation system.

3.4.2. Pinch point

The second law efficiency for the waste heat power generation system decreases with pinch point as illustrated in Fig. 11. This is due to reduced steam generation and network output with increased pinch point values. With higher pinch point the temperature difference between gas and water/steam is also high resulting in high irreversibilities. The Second law efficiency of the system is sensitive to pinch point and the pinch point should be low for better performance based on second law point of view.

3.5. Effect of operating conditions on first and second law efficiencies

The variation of first law and second law efficiencies for the waste heat power generation system with pinch point and gas inlet temperature are demonstrated in Fig. 12. The variation of first law efficiency with pinch point is not so much compared to second law efficiency. This clearly demonstrates that the second analysis provides more details on the performance of the power generation system based on quality point of view. The second law efficiency is higher as it provides a measure of how efficiently the system is using thermodynamic resources based on quality point of view. The first law efficiency is low because the majority of the heat input is carried away in the condenser. The second law efficiency decreases with higher pinch point as work output is reduced due to lower steam generation. The effect of higher gas inlet temperature increases both first and second law efficiency as the additional "heat input" results in higher steam generation, network output and lower gas exit temperatures.

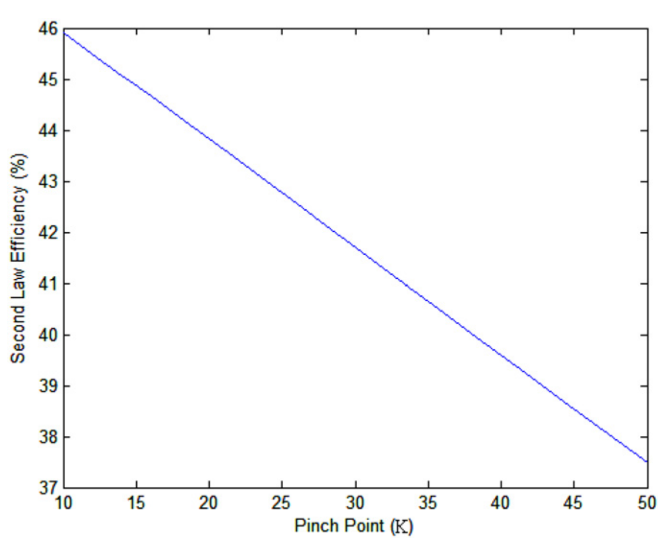

Fig. 11. Second law efficiency variation of waste heat power generation system; $\dot{m}_g = 100$ kg/s, $T_{g1} = 773$ K, $T_{s2} = 623$ K, $P = 60$ bar, Gas I: 4.42% CO_2, 16.55% O_2, 3.43% H_2O, 75.6% N_2.

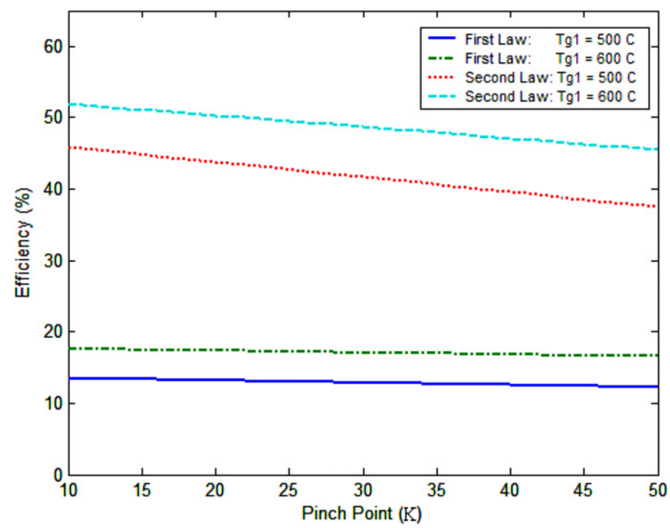

Fig. 12. Waste heat power generation system efficiency variation with pinch point and gas inlet temperature; $\dot{m}_g = 100$ kg/s, $T_{s2} = 623$ K, $P = 60$ bar, Gas I: 4.42% CO_2, 16.55% O_2, 3.43% H_2O, 75.6% N_2.

3.6. Validation with the published literature

The present results and trends for HRSG are along the lines reported in the literature by Karthikeyan et al. [9] and Ganapathy [3]. Nag and De [2] performed a second law analysis of an HRSG which focused on entropy generation number and sizing the HRSG for minimum irreversibility. Reddy et al. [11] reported that entropy generation number of an HRSG is modeling the gas as air. The present results apart from contributing the effect of pinch point, gas composition on entropy generation number and second law efficiency, are also along the lines of the results reported in the literature. The present work further contributes for better understanding of the role of gas composition, specific heat and pinch point on the performance of a waste heat recovery power generation system based on both first and second law of thermodynamics point of view.

4. Conclusion

Gas composition influences first law efficiency of the HRSG. The first law efficiency of the waste heat recovery power generation system increases with gas inlet temperature for the same pinch point and steam conditions. Air standard analysis provides a conservative estimate of first law efficiency. Second law performance of the power generation system is very sensitive to gas composition and large variations can occur if gas is approximated as air in the calculations.

The first and second law efficiencies of the HRSG and waste heat power generation system decreases with increasing pinch point. Pinch point is a dominant parameter governing performance and should be selected carefully.

Gas inlet temperature significantly increases second law efficiency of the HRSG and power generation system. For same pinch point, higher gas inlet temperatures result in increased heat recovery and the second law efficiency of the HRSG slightly improves with gas inlet temperature.

The second law analysis provides details of actual performance and is essential for thermodynamic optimization. The first and second law analyses are important tools for measuring performance by providing information on both how efficiently the energy input is converted to work output, and also how efficiently the thermodynamic resource are being used quality point of view. As interest on advanced energy systems increases, second law analysis aids to optimize their performance along with traditional energy methods.

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