THE AMBIENT TEMPERATURE INFLUENCE ON DEAERATOR EXERGY EFFICIENCY AND EXERGY LOSSES

PhD. Mrzljak Vedran[1], PhD. Orović Josip[2], PhD. Poljak Igor[2], PhD. Čulin Jelena[2]
[1]Faculty of Engineering, University of Rijeka, Vukovarska 58, 51000 Rijeka, Croatia
[2]University of Zadar, Maritime Department, M. Pavlinovića 1, 23000 Zadar, Croatia
E-mail: vedran.mrzljak@riteh.hr, jorovic@unizd.hr, ipoljak1@unizd.hr, jculin@unizd.hr

Abstract: *The exergy analysis of deaerator at three different steam power plant loads is performed in this paper. Also, the influence of the ambient temperature change on deaerator exergy efficiency and losses is analyzed. From the exergy viewpoint, deaerator operation shows the best characteristics at middle and high power plant loads. The lowest deaerator exergy destruction of 363.94 kW and the highest exergy efficiency of 93.27 % will be obtained at middle power plant load and at the ambient temperature of 5 °C. The highest deaerator exergy destruction of 1349.99 kW and the lowest exergy efficiency of 81.83 % will be obtained at low power plant load and at the ambient temperature of 45 °C. Deaerator operation is preferable at the lowest possible ambient temperature, regardless of the current power plant load.*

KEYWORDS: DEAERATOR, STEAM POWER PLANT, EXERGY ANALYSIS, THE AMBIENT TEMPERATURE CHANGE

1. Introduction

Steam power plants in general, regardless of their type, characteristics or developed power, has a complex condensate/feed water heating systems. Such systems are mounted between main steam condenser and steam generator. Its main function is condensate/feed water heating before it enters steam generator. Condensate/feed water heating is ensured with steam extracted from the main turbine. The usage of such systems results with fuel savings in steam generators and simultaneously with increasing of steam power plant overall efficiency.

In conventional high-power land based steam plants condensate/feed water heating systems can be assembled of a large number of components (heaters, pumps, and pressure reduction valves) [1], [2]. Number of components in condensate/feed water heating systems from marine steam power plants is much smaller due to insufficient space. This fact for marine steam power plants used in ship propulsion is valid regardless of the marine steam power plant has steam re-heating [3] or not [4].

Each condensate/feed water heating system is divided in two parts - the first part is a low-pressure condensate heating system and the second part is a high-pressure feed water heating system. The deaerator is a component which makes that division in any steam power plant. As any deaerator has a dual function (water heating and deaerating), it is very important for the entire steam system that deaerator operation is efficient and optimized.

In this paper, exergy analysis of deaerator from low-power cogeneration power plant is performed. Analyzed deaerator exergy efficiencies and losses were investigated at three different power plant loads, according to turbine developed power. The ambient temperature variation shows that exergy efficiencies and losses of the analyzed deaerator are sensibly dependent on the current ambient temperature.

2. Description and operation characteristics of deaerator from cogeneration power plant

The deaerator is a constituent component of any condensate/feed water heating system in any steam power plant [5], which is used for increasing condensate/feed water temperature before returning it to steam generator. Complete condensate/feed water heating system is therefore mounted between main steam condenser and steam generator.

Deaerator divides condensate/feed water heating system at two parts - first part is the low-pressure condensate heating system (between the main steam condenser [6] and deaerator) and the second part is the high-pressure feed water heating system (between deaerator and steam generator [7]).

In operation, deaerator has a dual function. The first function is condensate/feed water heating-deaerator is open condensate/feed water heater with direct mixing of water and superheated steam extracted from the main power plant turbine. The second deaerator function is to remove dissolved gases from condensate/feed water (deaerating) to prevent fast and intensive corrosion of steam system components and pipelines.

A deaerator analyzed in this paper, along with necessary operating points for the exergy analysis is presented in Fig. 1. Deaerator has four flow stream inputs: first is condensate flow stream from low-pressure condensate heating system (condensate is delivered to deaerator by condensate pump [8]), second is steam extracted from the main turbine, third is make-up water which is used to replenish the system with the lost water and finally fourth is condensate (condensate obtained from heating steam) from the first high-pressure feed water heater (this condensate is delivered to deaerator through pressure reduction valve [9]). Only output from the analyzed deaerator is feed water stream which passed through high-pressure feed water heating system for additional heating before entering the steam generator.

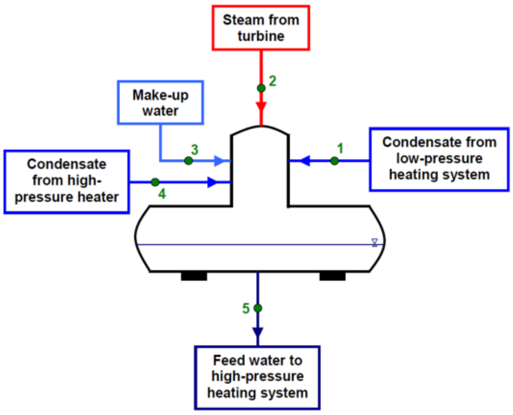

Fig. 1. *Scheme and operating points of the analyzed deaerator*

3. Deaerator exergy analysis

3.1. Exergy analysis equations for a control volume

The mass balance equation for any control volume in steady state, regardless of the number of inputs and outputs, can be defined according to [10] as:

$$\sum \dot{m}_{\mathrm{IN}} = \sum \dot{m}_{\mathrm{OUT}} \tag{1}$$

The main exergy balance equation for a control volume in steady state is defined according to [11] and [12] as:

$$\dot{X}_{\mathrm{heat}} - P = \sum \dot{m}_{\mathrm{OUT}} \cdot \varepsilon_{\mathrm{OUT}} - \sum \dot{m}_{\mathrm{IN}} \cdot \varepsilon_{\mathrm{IN}} + \dot{E}_{\mathrm{ex,D}} \tag{2}$$

Where the exergy transfer by heat ($\dot{X}_{\mathrm{heat}}$) at temperature T can be defined according to [13] by an equation:

$$\dot{X}_{\mathrm{heat}} = \sum (1 - \frac{T_0}{T}) \cdot \dot{Q} \tag{3}$$

Specific exergy, similar to specific enthalpy, represents a heat content of any fluid flow with taking into account the conditions of the ambient in which fluid flow operates (specific enthalpy does not take into account the ambient conditions). According to [14], specific exergy can be defined as:

$$\varepsilon = (h - h_0) - T_0 \cdot (s - s_0) \tag{4}$$

The exergy power of any fluid flow can be defined, according to [15] as:

$$\dot{E}_{\mathrm{ex}} = \dot{m} \cdot \varepsilon = \dot{m} \cdot \left[(h - h_0) - T_0 \cdot (s - s_0) \right] \tag{5}$$

The exergy efficiency definition depends on the type and operation principle of a control volume. In general, exergy efficiency can be defined according to [16] by an equation:

$$\eta_{\mathrm{ex}} = \frac{\text{Exergy output}}{\text{Exergy input}} \tag{6}$$

3.2. Exergy analysis equations of deaerator, according to presented operating points

For the deaerator analyzed in this paper, exergy analysis equations are defined according to operating points from Fig. 1. Deaerator exergy analysis equations are written in the same manner as exergy analysis equations for any other open heater (heater with two fluids mixing).

Deaerator mass balance:

$$\dot{m}_5 = \dot{m}_1 + \dot{m}_2 + \dot{m}_3 + \dot{m}_4 \tag{7}$$

Deaerator exergy balance:

→ Exergy power input:

$$\dot{E}_{\mathrm{ex,IN}} = \dot{m}_1 \cdot \varepsilon_1 + \dot{m}_2 \cdot \varepsilon_2 + \dot{m}_3 \cdot \varepsilon_3 + \dot{m}_4 \cdot \varepsilon_4 \tag{8}$$

→ Exergy power output:

$$\dot{E}_{\mathrm{ex,OUT}} = \dot{m}_5 \cdot \varepsilon_5 \tag{9}$$

→ Exergy destruction:

$$\begin{aligned} \dot{E}_{\mathrm{ex,D}} &= \dot{E}_{\mathrm{ex,IN}} - \dot{E}_{\mathrm{ex,OUT}} = \\ &= \dot{m}_1 \cdot \varepsilon_1 + \dot{m}_2 \cdot \varepsilon_2 + \dot{m}_3 \cdot \varepsilon_3 + \dot{m}_4 \cdot \varepsilon_4 - \dot{m}_5 \cdot \varepsilon_5 \end{aligned} \tag{10}$$

→ Exergy efficiency:

$$\eta_{\mathrm{ex}} = \frac{\dot{E}_{\mathrm{ex,OUT}}}{\dot{E}_{\mathrm{ex,IN}}} = \frac{\dot{m}_5 \cdot \varepsilon_5}{\dot{m}_1 \cdot \varepsilon_1 + \dot{m}_2 \cdot \varepsilon_2 + \dot{m}_3 \cdot \varepsilon_3 + \dot{m}_4 \cdot \varepsilon_4} \tag{11}$$

4. Deaerator operating parameters at three different loads

The deaerator is analyzed at three cogeneration power plant loads (low load, middle load and high load). Data for the deaerator analysis (temperatures, pressures and mass flows) of each fluid stream flow, according to Fig. 1, at each power plant load were found in [17]. The power plant load is directly proportional to main steam turbine produced power which amounts 24.3 MW at low plant load, 27.3 MW at middle plant load and 27.5 MW at high plant load.

At each power plant load, for every fluid stream flow (analyzed deaerator fluid streams are condensate/feed water and steam) specific enthalpies and specific exergies were calculated with NIST REFPROP 9.0 software [18] (by using temperature and pressure of each fluid stream).

Data for the deaerator analysis are presented in Table 1 for power plant low load, in Table 2 for power plant middle load and in Table 3 for power plant high load.

Specific exergies of each deaerator fluid stream (in each operating point from Fig. 1) depend on the ambient conditions. Data for the deaerator analysis are presented for the ambient pressure of 1 bar and the ambient temperature of 25 °C, as proposed in [19]. This ambient state is considered as a base state.

First, the deaerator exergy analysis is performed for the base state (at all observed power plant loads). After that, the same deaerator exergy analysis is performed at different temperatures. The ambient temperature range in which the deaerator was analyzed is selected on the basis of the real expected ambient temperature change for the cogeneration power plant through the whole calendar year. During the ambient temperature change, ambient pressure was kept constant (and equal to 1 bar), because in real power plant operating conditions significant change in the ambient pressure cannot be expected.

Table 1. *Deaerator operating parameters-low power plant load*

OP*	Temperature (°C)	Pressure (bar)	Mass flow (kg/s)	Specific enthalpy (kJ/kg)	Specific exergy (kJ/kg)
1	111.45	5	68.528	467.8	44.671
2	201.48	5	7.250	2859.0	756.330
3	24.98	5	12.056	105.2	0.401
4	151.83	5	8.778	876.7	160.590
5	151.83	5	96.611	640.4	90.068

* OP = Operating Point (according to Fig. 1)

Table 2. *Deaerator operating parameters-middle power plant load*

OP*	Temperature (°C)	Pressure (bar)	Mass flow (kg/s)	Specific enthalpy (kJ/kg)	Specific exergy (kJ/kg)
1	115.29	8.6	25.583	484.3	48.736
2	247.58	8.6	2.889	2943.0	862.450
3	24.97	8.6	0.972	105.5	0.762
4	169.89	7.9	2.750	932.9	184.850
5	173.27	8.6	32.194	733.4	119.700

* OP = Operating Point (according to Fig. 1)

Table 3. *Deaerator operating parameters-high power plant load*

OP*	Temperature (°C)	Pressure (bar)	Mass flow (kg/s)	Specific enthalpy (kJ/kg)	Specific exergy (kJ/kg)
1	110.97	7.9	26.556	466.0	44.504
2	223.45	7.9	3.111	2893.0	830.460
3	24.99	7.9	1.000	105.5	0.692
4	169.89	7.9	2.944	932.9	184.850
5	169.89	7.9	33.611	719.8	115.160

* OP = Operating Point (according to Fig. 1)

5. Deaerator exergy analysis results and discussion

5.1. Deaerator exergy analysis results at the ambient base state

At the base ambient state (25 °C and 1 bar), deaerator exergy power input and output are the highest at low plant load, Fig. 2. An increase in power plant load (from low to middle load) resulted with a significant decrease in the deaerator exergy power input and output, while a further increase in plant load (from middle to high load) resulted with a slight increase in both deaerator exergy power input and output.

At the observed power plant loads, range of deaerator exergy power input change is between 9959.06 kW and 4247.43 kW, while the range of deaerator exergy power output change is between 8701.57 kW and 3853.68 kW, Fig. 2.

At the base ambient state during the increase in power plant load, deaerator exergy destruction change is directly proportional to change in deaerator exergy power input and output, Fig. 2 and Fig. 3. At low power plant load, deaerator exergy destruction is the highest and amounts 1257.49 kW. An increase in power plant load from low to middle load resulted with a significant decrease in deaerator exergy destruction. At middle plant load deaerator exergy destruction is the lowest and amounts 393.76 kW, Fig. 3. Further increase in plant load (from middle to high load) resulted with a slight increase in deaerator exergy destruction (from 393.76 kW at middle to 439.80 kW at high plant load).

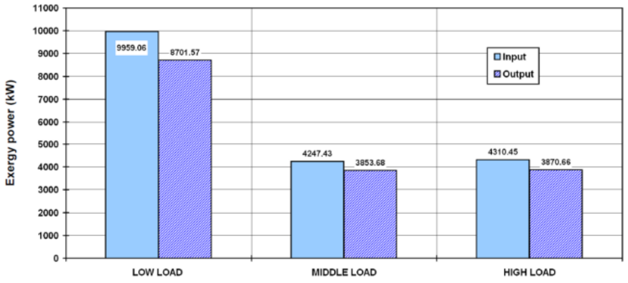

Fig. 2. *Change in analyzed deaerator exergy power inputs and outputs at three different power plant loads (base state)*

The lowest deaerator exergy efficiency can be seen at low power plant load, Fig. 3. An increase in power plant load from low to middle load resulted with a significant increase in deaerator exergy efficiency (from 87.37 % at low to 90.73 % at middle plant load). From middle to high power plant load, deaerator exergy efficiency slightly decreases (from 90.73 % at middle to 89.80 % at high load).

According to presented results, at the base ambient state, the deaerator optimal operation will surely be at middle plant load because at that plant load deaerator has the lowest exergy destruction and the highest exergy efficiency. Operation at high plant load will also be acceptable for the deaerator - at high power plant load deaerator exergy destruction is just slightly higher and exergy efficiency is just slightly lower than at the middle plant load.

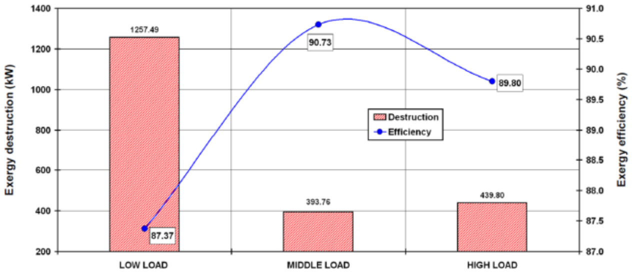

Fig. 3. *Change in deaerator exergy destruction and efficiency at three different power plant loads (base state)*

5.2. Deaerator exergy analysis results during the ambient temperature change

Change in the ambient temperature shows that deaerator exergy destruction increases with an increase in the ambient temperature (and simultaneously decreases with a decrease in the ambient temperature), Fig. 4. Ambient temperature was varied between 5 °C and 45 °C, which is expected ambient temperature change through the whole calendar year for observed cogeneration power plant in which analyzed deaerator operates.

As can be seen from Fig. 4, the highest deaerator exergy destructions, regardless of the ambient temperature, are at low power plant load. The lowest deaerator exergy destructions are obtained at middle plant load, while at the high power plant load deaerator exergy destructions are slightly higher when compared to middle plant load.

In the observed ambient temperature range (from 5 °C to 45 °C), deaerator exergy destruction shows the highest change of 185.04 kW at low power plant load. At middle power plant load, in the observed ambient temperature range, deaerator exergy destruction shows change of 59.79 kW, while at high plant load deaerator exergy destruction change is equal to 54.32 kW.

Deaerator operation at low plant load is highly influenced by the ambient temperature change (change of the ambient temperature for 10 °C resulted with a change in deaerator exergy destruction for 46.26 kW in average), while deaerator operation at high plant load is lowly influenced by the ambient temperature change (change of the ambient temperature for 10 °C resulted with a change in deaerator exergy destruction for 13.58 kW in average). At middle power plant load, change of the ambient temperature for 10 °C results with a change in deaerator exergy destruction for 14.95 kW in average.

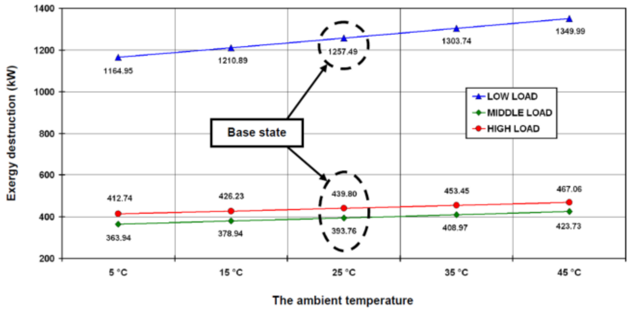

Fig. 4. *Change in deaerator exergy destruction for various ambient temperatures at three different power plant loads*

Deaerator exergy efficiency decreases with the ambient temperature increase (and simultaneously increases with a decrease in the ambient temperature) at any observed power plant load, Fig. 5.

At any ambient temperature, the highest deaerator exergy efficiency can be seen at the middle power plant load, while the lowest deaerator exergy efficiency is noted at low plant load, Fig. 5. At high power plant load, deaerator exergy efficiency is slightly lower when compared to middle plant load, regardless of the ambient temperature.

In the observed ambient temperature range (between 5 °C and 45 °C) deaerator exergy efficiency shows the highest change of 9.23 % at the low power plant load and the lowest change of 6.24 % at middle power plant load. Between the observed ambient temperatures deaerator exergy efficiency at high plant load shows the change of 6.64 %.

Deaerator exergy efficiency at low plant load is highly influenced by the ambient temperature change (change of the ambient temperature for 10 °C resulted with a change in deaerator exergy efficiency for 2.31 % in average). Low plant load and high ambient temperatures are the worst combination for deaerator exergy efficiency - at low plant load and with an increase in the ambient temperature from 35 °C to 45 °C deaerator exergy efficiency will decrease for more than 3 %. Change of the ambient temperature for 10 °C results with a change in deaerator exergy efficiency for 1.56 % in average at middle plant load and for 1.66 % in average at high plant load.

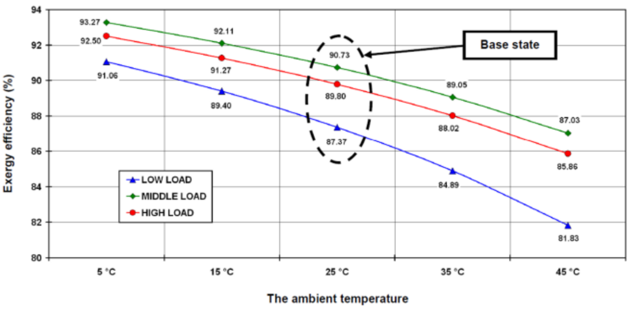

Fig. 5. *Change in deaerator exergy efficiency for various ambient temperatures at three different power plant loads*

A variation of the ambient temperature shows that deaerator operation will be preferable at the ambient temperature as low as possible.

From the viewpoint of power plant load, deaerator operation showed the best results at middle plant load (the highest exergy efficiencies and the lowest exergy destructions). High plant load showed that deaerator exergy efficiencies will be slightly lower and exergy destructions will be slightly higher in comparison with middle plant load. Deaerator operation at low plant load showed the worst results - long operation at this regime (from the viewpoint of analyzed deaerator) would be undesirable.

6. Conclusions

This paper presents an exergy analysis of deaerator from cogeneration steam power plant at three different plant loads. Data of the power plant operation enables calculation of deaerator exergy efficiencies and exergy destructions at each plant load. A variation of the ambient temperature (in the real expected ambient temperature range) shows that deaerator is very sensible from the viewpoint of exergy efficiencies and losses on the ambient temperature change. The most important conclusions of the presented analysis are:

- The lowest deaerator exergy destruction and the highest exergy efficiency are obtained at middle power plant load. At high power plant load deaerator exergy destruction is slightly higher and exergy efficiency is slightly lower when compared to middle plant load. Low plant load is the worst for deaerator operation: at low plant load deaerator has the highest destruction and the lowest exergy efficiency.
- The ambient temperature change shows that deaerator operation will be preferable at the lowest possible ambient temperature, because a decrease in the ambient temperature resulted with a decrease in deaerator exergy destruction and with an increase in a deaerator efficiency at any power plant load (and vice versa).
- The lowest deaerator exergy destruction which amount 363.94 kW and the highest exergy efficiency (93.27 %) will be obtained at middle power plant load and at the ambient temperature of 5 °C.
- The highest deaerator exergy destruction (1349.99 kW) and the lowest exergy efficiency (81.83 %) will be obtained at low power plant load and at the ambient temperature of 45 °C.
- From the viewpoint of the analyzed deaerator, low plant load is the operating regime which should be avoided during the majority of the power plant operation period.

7. Acknowledgment

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8. Nomenclature

Latin Symbols:		***Greek symbols:***	
$\dot{E}$	the total exergy flow, kW	ε	specific exergy, kJ/kg
h	specific enthalpy, kJ/kg	η	efficiency,
$\dot{m}$	mass flow rate, kg/s		
p	pressure, bar	***Subscripts:***	
P	power, kW	0	ambient state
$\dot{Q}$	heat transfer, kW	D	destruction (ex. loss)
s	specific entropy, kJ/kg·K	ex	exergy
T	temperature, °C or K	IN	inlet (input)
$\dot{X}_{\mathrm{heat}}$	heat exergy transfer, kW	OUT	outlet (output)

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CONTENTS

TECHNOLOGICAL BASIS OF “INDUSTRY 4.0”. DOMINANT TECHNOLOGIES IN “INDUSTRY 4.0”

BUSINESS & “INDUSTRY 4.0”. SOCIETY & „INDUSTRY 4.0”