# THERMODYNAMICAL ANALYSIS OF HEAT EXCHANGE AND FUEL CONSUMPTION IN MARINE RE-HEAT STEAM GENERATOR

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***Abstract:*** *The paper presents analysis of heat exchange and fuel consumption in the entire Marine Steam Generator (MSG) with steam re-heating and in all of its components. Analysis is performed by using operating parameters from the steam generator exploitation. The highest heat amount transferred from combustion gases is used in the evaporator (48.17 % of the cumulative heat amount transferred in MSG). Proportionally, evaporator uses the highest fuel mass flow of 0.5172 kg/s when compared to other MSG components. In the high-pressure pipeline heat losses amounts 82.64 kW. Cumulative heat transferred from combustion gases to water/steam in all MSG components amounts 42048.47 kW. Cumulative water/steam specific entropy and temperature increase in the entire MSG is 4.5677 kJ/kg·K and 454.18 K, while the fuel mass flow in the entire MSG is equal to 1.0736 kg/s.*

*KEYWORDS: MARINE STEAM GENERATOR, STEAM RE-HEATING, HEAT EXCHANGE, FUEL CONSUMPTION*

## *1. Introduction*

Marine propulsion systems are today mainly based on diesel engines, regardless of its type [1], [2]. Marine steam propulsion systems [3] still have a dominant role in the propulsion of LNG carriers. New propulsion systems for LNG carriers, which are at least partially based on steam turbines, are under development [4].

Marine steam propulsion systems have a high level of complexity due to a number of components from which they are assembled [5]. An essential element of such marine steam propulsion systems is steam generator. Older versions of marine steam generators produced superheated steam for all marine steam turbines [6] and for proper operation of other system components, but such steam generators do not posses ability of steam additional re-heating [7], [8]. Newer versions of marine steam generators possess that additional ability of steam re-heating.

In this paper is performed analysis of Marine Steam Generator (MSG) with additional steam re-heating. Analysis is based on the first law of thermodynamics. For each component of MSG with steam re-heating is calculated amount of heat transferred from combustion gases during the superheated steam production. Also, for each component of analyzed MSG is calculated fuel consumption. The analysis takes into account steam specific entropy and temperature increase on each analyzed MSG component along with heat and pressure losses of high-pressure steam pipeline.

## *2. Description of MSG with steam re-heating and its thermodynamic process*

Main scheme of Marine Steam Generator (MSG) with steam re-heating is presented in Fig. 1. Water which enters in MSG (point 1, Fig. 1) is heated in all steam generator components and from that water is produced superheated steam (point 2, Fig. 1). Heating in all MSG components is ensured with fuel burning (with the inevitable presence of air) which is delivered in steam generator furnace.

After production, main superheated steam is led through a high-pressure pipeline into the high-pressure turbine. Due to steam high pressure and temperature, heat and pressure losses in high-pressure pipeline cannot be neglected. Therefore, at the high-pressure turbine inlet (point 3, Fig. 1), superheated steam pressure and temperature are lower in comparison with outlet from the MSG (point 2, Fig. 1).

After expansion in the high-pressure turbine, steam was led back to the MSG for the re-heating process. Due to high-pressure steam turbine extractions, steam mass flow in re-heater is lower in comparison with the main steam mass flow. Re-heating process increases steam temperature (between points 4 and 5, Fig. 1) and after re-heating steam was lead to medium-pressure steam turbine.

Each steam generator consists of three main components in the same housing. Those components are water heater, evaporator and superheater. MSG from this analysis in the housing also has fourth component - steam re-heater. To be able to present heat transfer and fuel consumption of each MSG component, operating points from Fig. 1 are not sufficient, so between operating points 1 and 2 are added two additional operating points which divided MSG on its constituent components. That division is presented in Fig. 2.

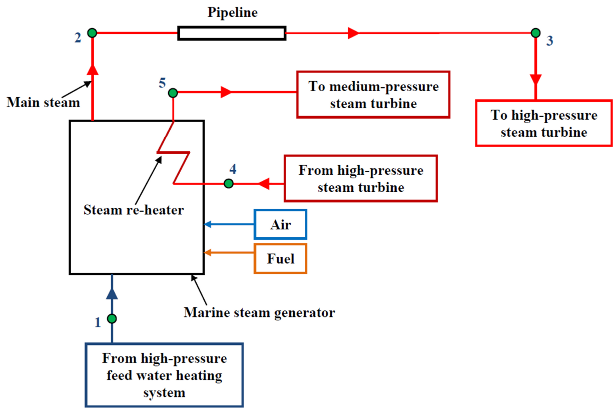


***Fig. 1.*** *Scheme of the MSG with marked operating points for the analysis*

Division of MSG into the components required some assumptions. The first assumption is that the process of water heating, evaporation and superheating is happening at the same pressure (pressure losses at each mentioned component is neglected). The second assumption is that water heating, evaporation and superheating processes begins or ends at the saturation line (for the evaporator process begins and ends at the saturation line), which varies from the real process. Only pressure loss which has taken into account is in re-heater due to high steam volume and speed through re-heater.

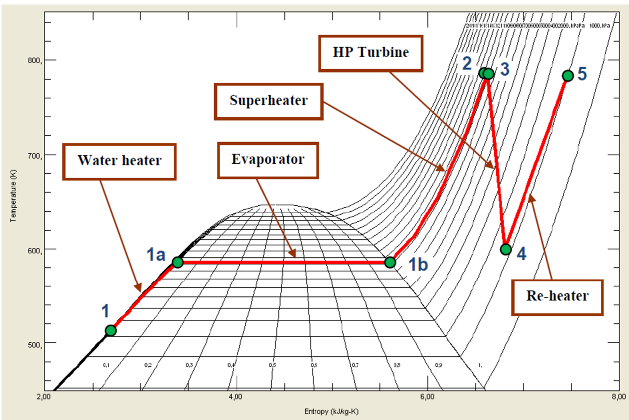


***Fig. 2.*** *T-s diagram of the MSG process with marked operating points necessary for the analysis of each component*

Besides analyzed process at each MSG component, in Fig. 2 can also be seen temperature (and pressure) loss in high-pressure steam pipeline (between points 2 and 3) as well as the real (polytropic) steam expansion process in a high-pressure steam turbine. The analysis in this paper ends with point 5, after steam exits the steam re-heater and was lead to medium-pressure steam turbine.

## *3. Equations for the thermodynamic analysis of MSG with steam re-heating*

Analysis of MSG is performed according to the first law of thermodynamics [9] which is related to the conservation of energy [10]. Equations for the analysis are defined according to Fig. 1 and Fig. 2:

- Heat transferred from combustion gases to water in the MSG water heater:

$$\dot{Q}_{\mathrm{WH}} = \dot{m}_1 \cdot (h_{1a} - h_1) \tag{1}$$

- MSG water heater fuel consumption:

$$\dot{m}_{\mathrm{f,WH}} = \frac{\dot{Q}_{\mathrm{WH}}}{H_{\mathrm{low}} \cdot \eta_{\mathrm{WH}}} = \frac{\dot{m}_1 \cdot (h_{1a} - h_1)}{H_{\mathrm{low}} \cdot \eta_{\mathrm{WH}}} \tag{2}$$

- Heat transferred from combustion gases to water/steam in MSG evaporator:

$$\dot{Q}_{\mathrm{EVAP}} = \dot{m}_{1a} \cdot (h_{1b} - h_{1a}) \tag{3}$$

- MSG evaporator fuel consumption:

$$\dot{m}_{\mathrm{f,EVAP}} = \frac{\dot{Q}_{\mathrm{EVAP}}}{H_{\mathrm{low}} \cdot \eta_{\mathrm{EVAP}}} = \frac{\dot{m}_{1a} \cdot (h_{1b} - h_{1a})}{H_{\mathrm{low}} \cdot \eta_{\mathrm{EVAP}}} \tag{4}$$

- Heat transferred from combustion gases to steam in MSG superheater:

$$\dot{Q}_{\mathrm{SH}} = \dot{m}_{1b} \cdot (h_2 - h_{1b}) \tag{5}$$

- MSG superheater fuel consumption:

$$\dot{m}_{\mathrm{f,SH}} = \frac{\dot{Q}_{\mathrm{SH}}}{H_{\mathrm{low}} \cdot \eta_{\mathrm{SH}}} = \frac{\dot{m}_{1b} \cdot (h_2 - h_{1b})}{H_{\mathrm{low}} \cdot \eta_{\mathrm{SH}}} \tag{6}$$

- Heat transferred from combustion gases to steam in MSG re-heater:

$$\dot{Q}_{\mathrm{RH}} = \dot{m}_4 \cdot (h_5 - h_4) \tag{7}$$

- MSG re-heater fuel consumption:

$$\dot{m}_{\mathrm{f,RH}} = \frac{\dot{Q}_{\mathrm{RH}}}{H_{\mathrm{low}} \cdot \eta_{\mathrm{RH}}} = \frac{\dot{m}_4 \cdot (h_5 - h_4)}{H_{\mathrm{low}} \cdot \eta_{\mathrm{RH}}} \tag{8}$$

- Heat loss in MSG high-pressure pipeline:

$$\dot{Q}_{\mathrm{PL}} = \dot{m}_2 \cdot (h_2 - h_3) \tag{9}$$

- Heat transferred from combustion gases to water/steam in the entire MSG:

$$\begin{aligned}\dot{Q}_{\mathrm{MSG}} &= \dot{m}_1 \cdot (h_2 - h_1) + \dot{m}_4 \cdot (h_5 - h_4) = \\ &= \dot{Q}_{\mathrm{WH}} + \dot{Q}_{\mathrm{EVAP}} + \dot{Q}_{\mathrm{SH}} + \dot{Q}_{\mathrm{RH}}\end{aligned} \tag{10}$$

- Entire MSG fuel consumption:

$$\begin{aligned}\dot{m}_{\mathrm{f,MSG}} &= \frac{\dot{Q}_{\mathrm{MSG}}}{H_{\mathrm{low}} \cdot \eta_{\mathrm{MSG}}} = \frac{\dot{m}_1 \cdot (h_2 - h_1) + \dot{m}_4 \cdot (h_5 - h_4)}{H_{\mathrm{low}} \cdot \eta_{\mathrm{MSG}}} = \\ &= \frac{\dot{Q}_{\mathrm{WH}} + \dot{Q}_{\mathrm{EVAP}} + \dot{Q}_{\mathrm{SH}} + \dot{Q}_{\mathrm{RH}}}{H_{\mathrm{low}} \cdot \eta_{\mathrm{MSG}}}\end{aligned} \tag{11}$$

Data for the MSG thermodynamic analysis were found in [5]. In this document the authors specified that used fuel have a lower heating value ($H_{\mathrm{low}}$) equal to 43038 kJ/kg and steam generator efficiency ($\eta_{\mathrm{MSG}}$) is 91 %. In this analysis were taken the same fuel lower heating value, while the efficiency of 91 % is assumed for the entire MSG and each of its components. Water/steam specific enthalpies (*h*) and specific entropies (*s*) were calculated with NIST REFPROP 9.0 software [11] from known temperature and pressure at each operating point of Fig. 1 and Fig. 2.

## *4. Operating parameters at each MSG point necessary for the analysis*

Water/steam temperature, pressure and mass flow at each operating point of MSG (Fig. 1) were found in [5] and presented in Table 1. In Table 1 are also presented water/steam specific enthalpies and specific entropies calculated with NIST REFPROP 9.0 software [11] at each observed MSG operating point.

***Table 1.*** *Data for the MSG analysis at each operating point [5]*

| Op. point* | Temperature (K) | Pressure (kPa) | Mass flow (kg/s) | Specific enthalpy (kJ/kg) | Specific entropy (kJ/kg·K) |
|---|---|---|---|---|---|
| **1** | 514.87 | 10300 | 15.593 | 1046.5 | 2.7028 |
| **2** | 786.00 | 10300 | 15.593 | 3404.6 | 6.6247 |
| **3** | 783.00 | 10100 | 15.593 | 3399.3 | 6.6263 |
| **4** | 599.95 | 2260 | 12.859 | 3079.2 | 6.8087 |
| **5** | 783.00 | 2030 | 12.859 | 3489.7 | 7.4545 |

* Operating point numeration refers to Fig. 1 and Fig. 2

Analysis of heat transfer and fuel consumption at each MSG component requires widening of data between operating points 1 and 2 (Fig. 1). Operating points 1 and 2 has the same pressure (Table 1), so at each main component of the analyzed MSG (re-heater not included) is assumed the same pressure of 10300 kPa. Through each MSG component the water/steam mass flow is equal (15.593 kg/s). Widening of operating data is performed according to Fig. 2 (new added operating points are 1a and 1b) to be able to analyze each MSG component individually. Operation parameters for all added operating points are presented in Table 2.

***Table 2.*** *Expanded data for the MSG analysis between operating points 1 and 2*

| Op. point* | Temperature (K) | Pressure (kPa) | Mass flow (kg/s) | Specific enthalpy (kJ/kg) | Specific entropy (kJ/kg·K) |
|---|---|---|---|---|---|
| **1** | 514.87 | 10300 | 15.593 | 1046.5 | 2.7028 |
| **1a** | 586.33 | 10300 | 15.593 | 1420.9 | 3.3819 |
| **1b** | 586.33 | 10300 | 15.593 | 2719.9 | 5.5974 |
| **2** | 786.00 | 10300 | 15.593 | 3404.6 | 6.6247 |

* Operating point numeration refers to Fig. 2

## *5. The results of the MSG with steam re-heating thermodynamic analysis*

Heat transferred from combustion gasses to operating medium (operating medium is water/steam) at each analyzed MSG component, along with heat losses in the high-pressure pipeline is presented in Fig. 3. In high-pressure pipeline occurs decrease of steam pressure (Table 1) and simultaneous decrease in steam temperature which resulted with heat losses equal to 82.64 kW. Heat losses also occur in all the other steam pipelines, but in high-pressure steam pipeline heat losses are the highest (due to the highest steam pressure and temperature), so it should not be neglected as in other pipelines.

Heat transfer at MSG components shows that the highest heat amount of 20255.31 kW is transferred from combustion gases to operating medium in evaporator during the change in water aggregate state (from water to saturated steam). Superheater is the second heat consumer which increases saturated steam temperature and for that temperature increase uses heat amount of 10676.53 kW. In the analyzed MSG, water heater uses a higher heat amount of combustion gases than re-heater (5838.02 kW for water heater and 5278.62 kW for re-heater). The main reason for such occurrence is that water mass flow, which passes through water heater, is notably higher when compared with superheated steam mass flow, which passes through the re-heater, Table 1. Heat transferred in the entire analyzed MSG (water heater, evaporator, superheater and re-heater) amounts 42048.47 kW, Fig. 3.

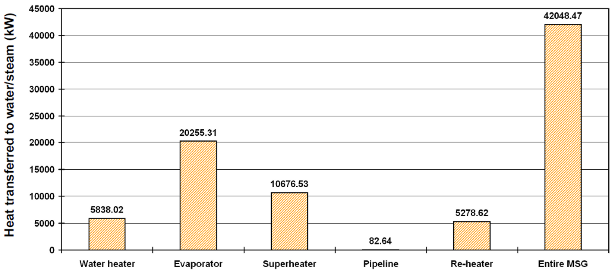


***Fig. 3.*** *Distribution of heat transferred from combustion gases in all analyzed MSG components along with heat loss in the high-pressure pipeline*

From the entire heat amount which is transferred from combustion gases to water/steam in the analyzed MSG, 48.17 % is used by the evaporator, Fig. 4. After evaporator, 25.39 % of the cumulative transferred heat amount uses superheater, water heater uses 13.88 % and the lowest percentage of the cumulative transferred heat amount uses re-heater (12.55 %).

Analyzed MSG acts as many other marine steam generators and steam generators from the land-based steam power plants because the largest heat amount is used for changing the water aggregate state. Change of water aggregate state, according to early adopted assumptions did not result in water/steam temperature increase in evaporator (water/steam temperature in the evaporator can only decrease due to losses).

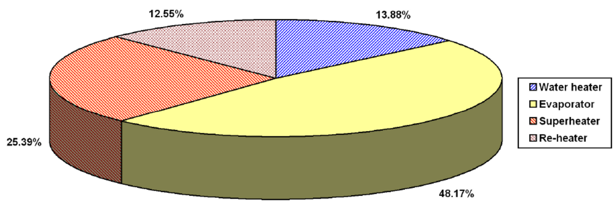


***Fig. 4.*** *Percentage distribution of transferred heat in all MSG components*

Increase of water/steam specific entropy in the analyzed MSG is the highest in the evaporator after which follows the superheater, two components which uses the highest delivered heat amount, Fig. 4 and Fig. 5. Increase in specific entropy of operating medium is higher for water heater than for re-heater, Fig. 5. From this observation can be concluded that heat transferring process in the components of analyzed MSG is directly proportional to operating medium specific entropy increment - increase in delivered heat amount from combustion gases is followed by a proportional increase in specific entropy.

The increase in operating medium temperature of analyzed MSG is not proportional to heat transfer process, Fig. 4 and Fig. 5. Evaporator which gets the highest heat amount of burned fuel does not increase water/steam temperature because of the aggregate state change. The highest operating medium temperature increase can be seen in superheater and re-heater, which both increase temperature of superheated steam (superheater for 199.67 K and re-heater for 183.05 K). MSG water heater increases water temperature for 71.46 K, Fig. 5.

The sum of operating medium specific entropy and temperature increment at each analyzed MSG component resulted with a conclusion that analyzed MSG increases the specific entropy of operating medium for a cumulative value of 4.5677 kJ/kg·K, while the cumulative increase in operating medium temperature in this steam generator is equal to 454.18 K.

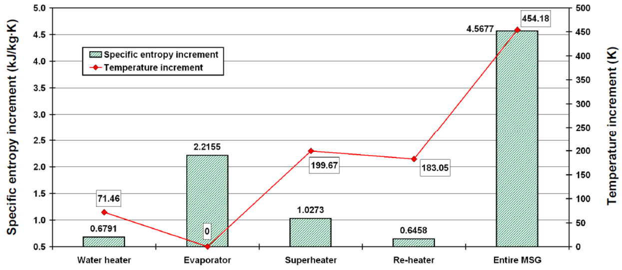


***Fig. 5.*** *Increase in water/steam specific entropy and temperature in each component and in the entire MSG*

Fuel consumption for each MSG component is also directly proportional to heat transferred on each component, Fig. 6. The highest fuel consumer (and proportionally the highest heat consumer) is evaporator which uses fuel mass flow of 0.5172 kg/s. After the evaporator follows superheater and water heater which uses fuel mass flow of 0.2726 kg/s and 0.1491 kg/s. The lowest fuel mass flow (and proportionally the lowest heat amount) of all analyzed MSG components can be seen at re-heater which uses fuel mass flow of 0.1348 kg/s. All the MSG components use the same fuel, which lower heating value amounts 43038 kJ/kg.

Cumulative fuel mass flow used in the entire analyzed MSG is the sum of fuel mass flows used in each component. Fuel mass flow in the entire MSG is 1.0736 kg/s, Fig. 6.

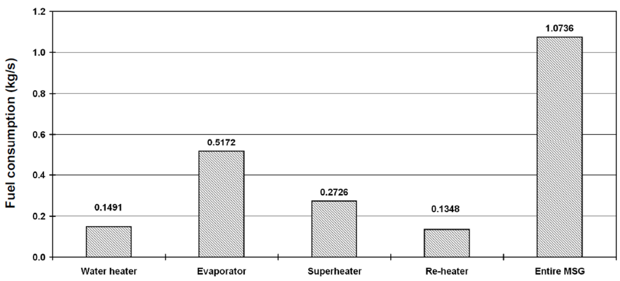


***Fig. 6.*** *Fuel consumption for each component and in the entire MSG*

NIST REFPROP 9.0 software [11] allows calculation of many water/steam operating parameters (besides specific enthalpies and specific entropies) at each observed operating point of the analyzed MSG. Some of important water/steam operating parameters necessary for detail calculation of MSG operation is presented in Fig. 7. Those operating parameters are presented in each operating point of MSG according to Fig. 2.

Water/steam specific volume, which is directly proportional to operating medium volume, is one of the indicators for losses at each MSG component (especially pressure losses). In MSG water heater (points from 1 to 1a) increase in water specific volume is low, so pressure losses in that component can be neglected. In evaporator (points from 1a to 1b) and in superheater (points from 1b to 2) increase in operating medium specific volume is significant and in that MSG components can be expected a notable operating medium pressure decrease during MSG operation, which are neglected in this analysis (according to used operating parameters from [5]). So, in the real exploitation of analyzed MSG will be important precise measurements of steam pressure and temperature at the evaporator and superheater inlets and outlets, if possible. Temperature and pressure decrease in high-pressure pipeline (points from 2 to 3) resulted with an increase in superheated steam specific volume from 0.03250 $m^3$/kg to 0.03302 $m^3$/kg. The most significant increase in superheated steam specific volume can be seen during the steam expansion in the high-pressure turbine (points from 3 to 4) and in steam re-heater (points from 4 to 5). Such significant increase in superheated steam specific volume through the MSG re-heater resulted in steam pressure decrease between re-heater inlet (operating point 4) and outlet (operating point 5), which can be seen in Table 1.

Compressibility factor denotes the difference between the real and ideal gas. Compressibility factor value equal to 1 denotes an ideal gas, while its value lower than or greater than 1 represents the real gas. Compressibility factor is usually used to observe how much the current operating medium characteristics deviate from the ideal gas. For the analyzed MSG in the water heater (points from 1 to 1a) operating medium characteristics significantly deviates from ideal gas because in water heater operating medium is water, so compressibility factor is 0.05299 at the water heater inlet and 0.05569 at the water heater outlet. Saturated steam at the evaporator outlet (operating point 1b) has compressibility factor 0.66152 which means that saturated steam characteristics getting closer to an ideal gas (in comparison with water in water heater). At the superheater outlet (operating point 2) superheated steam has a compressibility factor equal to 0.92266, what indicates that superheated steam has a characteristics very close to ideal gas. After the expansion in high-pressure steam turbine (at the re-heater inlet-operating point 4) superheated steam has a compressibility factor of 0.95199, while at the re-heater outlet (operating point 5) superheated steam has a compressibility factor of 0.98525.

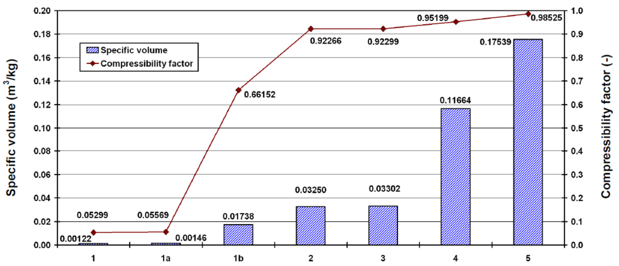


***Fig. 7.** Change in water/steam specific volume and compressibility factor at each analyzed MSG operating point*

## 6. Conclusions

This paper presents analysis of heat exchange and fuel consumption in Marine Steam Generator (MSG) with steam re-heating and in all of its constituent components. The presented analysis provides insight into the operation of each MSG component and presented the most important temperature and pressure losses during the superheated steam production. The most important conclusions of this analysis are:

- The highest transferred heat amount of the entire analyzed MSG is used in the evaporator and amounts 20255.31 kW (48.17 % of the cumulative heat amount transferred in MSG).
- The lowest transferred heat amount of the entire analyzed MSG is used in steam re-heater and amounts 5278.62 kW (12.55 % of the cumulative heat amount transferred in MSG) due to lower operating medium mass flow through re-heater when compared to other MSG components.
- Due to the highest transferred heat amount, evaporator uses the highest fuel mass flow, which amounts 0.5172 kg/s and causes the highest specific entropy increase of operating medium (2.2155 kJ/kg·K), when compared to other MSG components.
- The highest operating medium temperature increase occurs in superheater and re-heater (superheater for 199.67 K and re-heater for 183.05 K), while the evaporator uses the highest heat amount but did not increase operating medium temperature (in evaporator operating medium change its aggregate state).
- Superheated steam, after it leaves MSG superheater, has characteristics very similar to ideal gases.
- Cumulative heat transferred from combustion gases to water/steam in all MSG components (in the entire MSG) amounts 42048.47 kW. Cumulative water/steam specific entropy and temperature increase in the entire analyzed MSG is 4.5677 kJ/kg·K and 454.18 K, while the fuel mass flow in the entire MSG is 1.0736 kg/s.

## 7. Acknowledgments

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## 8. Nomenclature

| | | | |
|---|---|---|---|
| **Abbreviations:** | | **Greek symbols:** | |
| MSG | Marine Steam Generator | $\eta$ | efficiency, % |
| **Latin symbols:** | | **Subscripts:** | |
| $h$ | specific enthalpy, kJ/kg | EVAP | Evaporator |
| $H_{low}$ | fuel lower heating value, kJ/kg | f | fuel |
| $\dot{m}$ | mass flow, kg/s | PL | Pipeline Loss |
| $p$ | pressure, kPa | RH | Re-Heater |
| $\dot{Q}$ | heat transfer, kW | SH | Super Heater |
| $s$ | specific entropy, kJ/kg·K | WH | Water Heater |
| $T$ | temperature, K | | |

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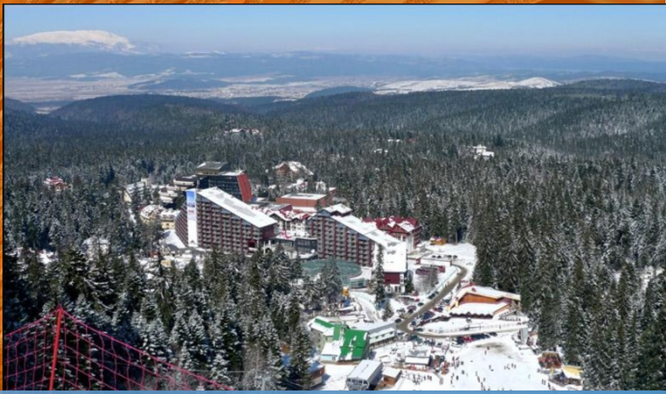

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