# ANALYSIS OF TWO METHODS FOR STEAM TURBINE DEVELOPED POWER CALCULATION IN INDUSTRY 4.0

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## Abstract:

The paper presents analysis of two methods for steam turbine developed power calculation (direct and indirect method) which can be a useful element in Industry 4.0 concept. Four different steam turbines from the literature was selected and both power calculation methods are tested on each of them. Both methods give the same results, but they don't use the same parameters in developed power calculation. Steam turbine developed power depends on steam specific enthalpies, but the major influence on any steam turbine developed power has steam mass flow rate.

***Keywords:*** Power production, Steam turbine, Industry 4.0, Calculation methods

## 1. Introduction

The concept of Industry 4.0 involves many different elements (and problems which can occur) in manufacturing technologies. Some of those elements included artificial intelligence [1], [2], vibrations and thermal stress in rotary machines [3], [4], neural networks [5] and genetic algorithm [6].

One of the possible problems can also be power and electricity production. Power production by using steam turbines is the most usual power production, which is, in the most of cases, used for electricity generators drive. Proper calculation of steam turbine developed power and two methods which can be used in such calculation are presented and investigated in this paper.

## 2. Power production in Industry 4.0 concept

Power production in Industry 4.0 concept can be ensured with different power producer. Along with the most used steam turbines in different power plants [7-9] it can also be used internal combustion engines of any type and any kind [10-14], gas turbines and combined power plants which consist of at least one gas turbine and at least one steam turbine [15].

Any power producer has its own advantages and disadvantages. The most used steam turbines for power production are complex machines, composed of a significant number of different parts and steam flow streams throughout and outside the turbine. As the most used power producers, it is important to properly calculate steam turbine developed power in any possible operating regime.

## 3. Numerical description of two methods for steam turbine developed power calculation

In order to explain two methods for steam turbine developed power calculation, it is selected steam turbine with two steam extractions presented in Fig. 1. Necessary operating parameters of each developed power calculation method are steam mass flow rates and steam specific enthalpies at the turbine inlet, outlet and in each steam extraction [16]. In Fig. 1 and throughout this paper, steam parameters at the turbine inlet are marked with index in, steam parameters at the turbine outlet with index out and index ex denotes steam operating parameters at the turbine extraction. Along with index ex, for more than one steam extraction (as presented in Fig. 1), steam operating parameters are marked with additional number which describe ordinal number of extraction (counting from the turbine inlet to the turbine outlet). The numerical definition of both calculation methods for steam turbine developed power calculation will be based on turbine operating points from Fig. 1.

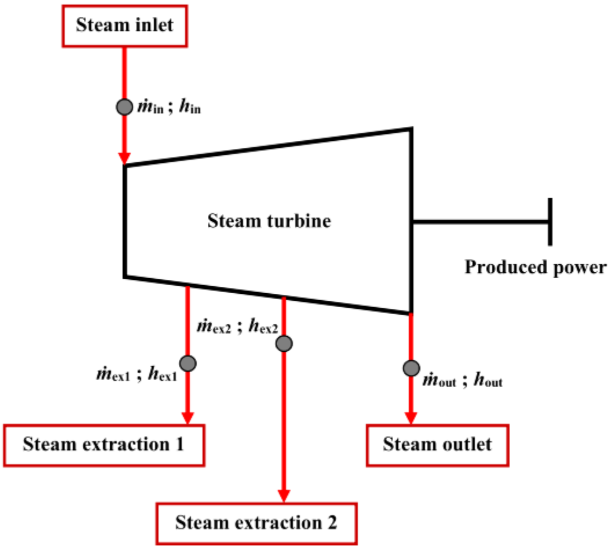


***Figure 1.*** *– Steam turbine with two steam extractions – defining of two methods for developed power calculation*

It should be noted that for low power steam turbines without steam extractions, both methods for a developed power calculation are the same and will resulted with the same equation [17], [18]. Both methods for the same steam turbine developed power calculation must give the same result in the same operating regime.

### 3.1. Direct method for steam turbine developed power calculation

Direct method for steam turbine developed power calculation is based on the steam mass flow rate through each turbine segment and on the steam specific enthalpy difference between each turbine segment inlet and outlet. Steam turbine from Fig. 1 has three segments:

1) Between turbine inlet (in) and first extraction (ex1),
2) Between first (ex1) and second (ex2) extraction,
3) Between second extraction (ex2) and turbine outlet (out).

A power developed in the entire turbine from Fig. 1 (with neglecting steam mass flow rates lost through front and rear gland seals), while using direct method is [19]:

$$P_{\mathrm{T}} = \dot{m}_{\mathrm{in}} \cdot (h_{\mathrm{in}} - h_{\mathrm{ex1}}) + (\dot{m}_{\mathrm{in}} - \dot{m}_{\mathrm{ex1}}) \cdot (h_{\mathrm{ex1}} - h_{\mathrm{ex2}}) + (\dot{m}_{\mathrm{in}} - \dot{m}_{\mathrm{ex1}} - \dot{m}_{\mathrm{ex2}}) \cdot (h_{\mathrm{ex2}} - h_{\mathrm{out}}), \tag{1}$$

with a note that steam mass flow rate through last turbine segment is equal to steam mass flow rate at the turbine outlet:

$$\dot{m}_{\mathrm{out}} = \dot{m}_{\mathrm{in}} - \dot{m}_{\mathrm{ex1}} - \dot{m}_{\mathrm{ex2}}. \tag{2}$$

In Eq. 1 ( $\dot{m}_{\mathrm{in}}$ ) is the steam mass flow rate through the first turbine segment, $(\dot{m}_{\mathrm{in}} - \dot{m}_{\mathrm{ex1}})$ is the steam mass flow rate through second turbine segment and ( $\dot{m}_{\mathrm{out}} = \dot{m}_{\mathrm{in}} - \dot{m}_{\mathrm{ex1}} - \dot{m}_{\mathrm{ex2}}$ ) is the steam mass flow rate through the third turbine segment, while $(h_{\mathrm{in}} - h_{\mathrm{ex1}})$ is steam specific enthalpy difference at the first turbine segment, $(h_{\mathrm{ex1}} - h_{\mathrm{ex2}})$ is a steam specific enthalpy difference at second turbine segment and $(h_{\mathrm{ex2}} - h_{\mathrm{out}})$ is a steam specific enthalpy difference at the third turbine segment.

The overall equation for any steam turbine developed power calculation by using direct method is:

$$P_{\mathrm{T}} = \sum_{1}^{n} \dot{m}_{\mathrm{segment}} \cdot \Delta h_{\mathrm{segment}}, \tag{3}$$

where *n* is the cumulative number of turbine segments which can be determined as:

*n* = (cumulative number of turbine extractions + 1). (4)

### 3.2. Indirect method for steam turbine developed power calculation

Indirect method for steam turbine developed power calculation is based on a calculation of turbine developed power without taking into account steam extractions (maximum turbine power) after which from obtained result is deducted lost turbine power of each extraction. The baseline for this method is using steam mass flow rate and specific enthalpy in each turbine operating point before the turbine outlet (Fig. 1) and steam specific enthalpy at the turbine outlet. This method does not require knowing the steam mass flow rate at the turbine outlet.

A power developed in the entire turbine from Fig. 1 (with neglecting steam mass flow rates lost through front and rear gland seals), while using indirect method is:

$$P_{\mathrm{T}} = \dot{m}_{\mathrm{in}} \cdot (h_{\mathrm{in}} - h_{\mathrm{out}}) - \dot{m}_{\mathrm{ex1}} \cdot (h_{\mathrm{ex1}} - h_{\mathrm{out}}) - \dot{m}_{\mathrm{ex2}} \cdot (h_{\mathrm{ex2}} - h_{\mathrm{out}}), \quad (5)$$

where [ $\dot{m}_{\mathrm{in}} \cdot (h_{\mathrm{in}} - h_{\mathrm{out}})$ ] is maximum turbine power, [ $\dot{m}_{\mathrm{ex1}} \cdot (h_{\mathrm{ex1}} - h_{\mathrm{out}})$ ] is lost turbine power of first extraction and [ $\dot{m}_{\mathrm{ex2}} \cdot (h_{\mathrm{ex2}} - h_{\mathrm{out}})$ ] is lost turbine power of second extraction. The overall equation for any steam turbine developed power calculation by using indirect method is:

$$P_{\mathrm{T}} = P_{\mathrm{max}} - \sum_{1}^{k} \dot{m}_{\mathrm{ex,i}} \cdot \left(h_{\mathrm{ex,i}} - h_{\mathrm{out}}\right), \quad (6)$$

where $i$ is index for each turbine extraction, and $k$ is the cumulative number of turbine extractions.

## 4. Selected steam turbines and their operating parameters

For developed power calculation by both observed methods (direct and indirect) it was selected four steam turbines from the literature. First two steam turbines (Turbine 1 and Turbine 2) are turbines with one steam extraction – Fig. 2(a) and the last two steam turbines (Turbine 3 and Turbine 4) are turbines with four steam extractions – Fig. 2(b). Steam extractions of each selected steam turbine are used for steam delivering into feed water heating system – in its low pressure part [20], [21] or high pressure part [22]. In some situations, any steam extraction can deliver steam to other heaters [23]. On each steam extraction are usually mounted pressure reduction valves, for regulation of steam pressure before its delivery to the heating device [24].

The first two steam turbines are back pressure turbines, which means that steam after the turbines has a pressure above the atmospheric one, while the last two turbines are condensation turbines and steam at the outlet of these turbines is delivered directly to a steam condenser (steam pressure at the turbine outlet is significantly lower in comparison with atmospheric pressure) [25].

At each operating point of all observed steam turbines is required knowledge of steam operating parameters (temperature, pressure and mass flow rate), which allows calculation of steam specific enthalpy required for power calculation in each of the observed power calculation methods. Steam specific enthalpies, for any of the observed turbine, in any operating point, are calculated by using NIST-REFPROP 9.0 software [26].

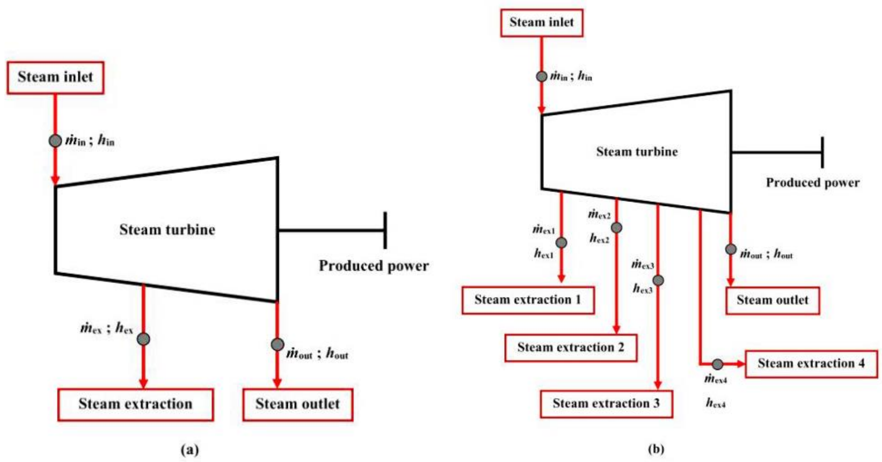


***Figure 2.*** *– (a) Steam turbine with one steam extraction; (b) Steam turbine with four steam extractions*

Turbine 1 is a high pressure cylinder of main marine propulsion steam turbine from LNG carrier [27], Fig. 2(a). It has one steam extraction. Such steam turbine is designed to be dynamic in operation in order to improve ship maneuverability. Steam operating parameters for Turbine 1 are presented in Table 1.

***Table 1.*** *– Steam operating parameters for Turbine 1*

| Operating point | Steam mass flow rate (kg/s) | Steam temperature (°C) | Steam pressure (MPa) |
|---|---|---|---|
| **inlet** | 26.798 | 500 | 5.899 |
| **extraction** | 0.908 | 350 | 1.565 |
| **outlet** | 25.891 | 256 | 0.593 |

Turbine 2 is a high pressure cylinder of complex steam turbine with several cylinders from steam power plant [28]. It also (as Turbine 1) has one steam extraction, Fig. 2(a). Steam operating parameters for Turbine 2 are presented in Table 2. Steam operating parameters for Turbine 2 presented in Table 2 are based on mass flow rate balance, with neglecting of steam mass flow rates lost through front and rear gland seals.

***Table 2.*** *– Steam operating parameters for Turbine 2*

| Operating point | Steam mass flow rate (kg/s) | Steam temperature (K) | Steam pressure (bar) |
|---|---|---|---|
| **inlet** | 327.60 | 766.5 | 138.10 |
| **extraction** | 17.63 | 584.7 | 42.32 |
| **outlet** | 309.97 | 537.4 | 28.68 |

Turbine 3 is a low pressure cylinder (from the two-cylinder steam turbine) which operates in a coal-fired power plant [29]. It has four steam extractions, Fig. 2(b). Steam operating parameters for Turbine 3 are presented in Table 3.

***Table 3.*** *– Steam operating parameters for Turbine 3*

| Operating point | Steam mass flow rate (kg/s) | Steam temperature (K) | Steam pressure (kPa) |
|---|---|---|---|
| **inlet** | 103.74 | 785.32 | 3580.00 |
| **extraction 1** | 6.97 | 737.41 | 2353.00 |
| **extraction 2** | 6.86 | 635.99 | 1100.00 |
| **extraction 3** | 7.12 | 484.66 | 250.00 |
| **extraction 4** | 4.87 | 459.62 | 180.00 |
| **outlet** | 77.92 | 316.09 | 8.63 |

Turbine 4 is single-cylinder steam turbine, which operates in steam power plant [30]. It has four steam extractions (as Turbine 3), Fig. 2(b). Steam operating parameters for Turbine 4 are presented in Table 4.

***Table 4.*** *– Steam operating parameters for Turbine 4*

| Operating point | Steam mass flow rate (kg/s) | Steam temperature (°C) | Steam pressure (bar) |
|---|---|---|---|
| **inlet** | 33.194 | 482.01 | 43.00 |
| **extraction 1** | 1.945 | 314.61 | 11.72 |
| **extraction 2** | 1.147 | 232.52 | 5.29 |
| **extraction 3** | 2.028 | 184.84 | 3.09 |
| **extraction 4** | 2.641 | 92.81 | 0.78 |
| **outlet** | 25.433 | 40.79 | 0.08 |

Steam for selected turbines operation is produced in steam generators (marine or land based steam generators) [31], and it can be also used for auxiliary steam turbine operation [32], [33]. Along with marine propulsion or electricity generator drive, one part of the power developed by observed steam turbines can be used for the operation of additional equipment in the steam plant [34].

## 5. Application of both presented methods on selected steam turbines and its power calculation

According to presented steam operating parameters for each observed turbine, calculated steam specific enthalpies in each operating point of each turbine are presented in Fig. 3 for Turbine 1 and Turbine 2 and in Fig. 4 for Turbine 3 and Turbine 4.

From Fig. 3 can be clearly seen that Turbine 1 in each operating point has a higher steam specific enthalpy when compared to steam specific enthalpy in each operating point of Turbine 2. Higher steam specific enthalpy of Turbine 1 does not mean that Turbine 1 develop higher power than Turbine 2 – power of each Turbine 1 and Turbine 2 also depends on steam mass flow rates through each turbine.

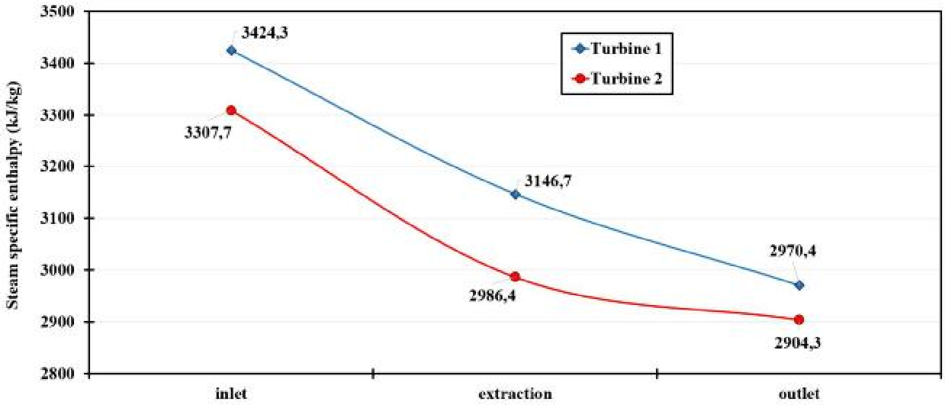


***Figure 3.*** *– Change in steam specific enthalpy of the analyzed Turbine 1 and Turbine 2*

Comparison of steam specific enthalpies in each operating point of Turbine 3 and Turbine 4 – Fig. 4, shows that Turbine 3 has higher steam specific enthalpy in each operating point when compared to Turbine 4. As both Turbine 3 and Turbine 4 are condensation steam turbines, steam specific enthalpy at the steam condenser entrance (turbine outlet) has a value lower than 2500 kJ/kg for both observed turbines.

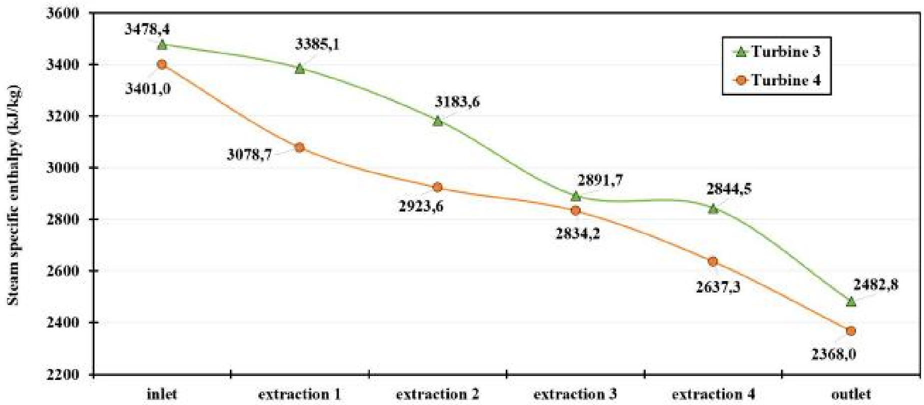


***Figure 4.*** *– Change in steam specific enthalpy of the analyzed Turbine 3 and Turbine 4*

After computing, both methods for steam turbine developed power calculation (direct and indirect) gave the same results for each of the four observed turbines. The results of developed power for each of four observed turbines are presented in Fig. 5.

Despite of lower steam specific enthalpy in each operating point (Fig. 3), Turbine 2 has significantly higher developed power then Turbine 1 due to significantly higher steam mass flow rate through the turbine (Table 2), not only when compared to Turbine 1 but also when compared to all the other observed turbines. Turbine 2 has the highest developed power of all observed steam turbines, Fig. 5.

Turbine 3 in each operating point has a higher steam specific enthalpy when compared to Turbine 4 (Fig. 4), but also has a significantly higher steam mass flow rate than Turbine 4 (Table 3 and Table 4) what resulted with significantly higher developed power, Fig. 5.

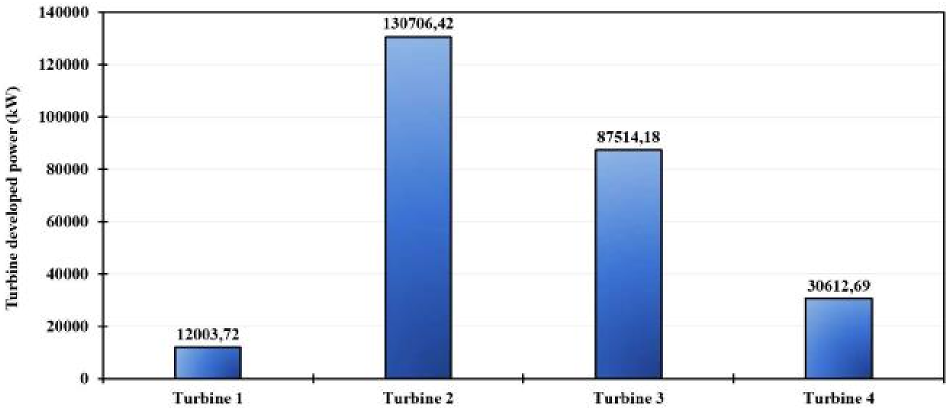


***Figure 5.*** *– Developed power of each observed turbine obtained with both calculation methods*

## 6. Conclusions

This paper presents an analysis of two methods for steam turbine developed power calculation as a useful tool in Industry 4.0. Two different methods are compared and discussed. It was randomly selected four different steam turbines from the literature and observed methods are investigated on all of them. It can be concluded that both methods give the same results, but with different calculation logic. The most important conclusions are:

- Direct method for steam turbine developed power calculation track steam mass flow rate through each turbine segment along with steam specific enthalpies at each turbine segment inlet and outlet.
- Indirect method for steam turbine developed power calculation takes into account maximum turbine developed power along with a deduction of the lost turbine power of each extraction. This method does not require knowledge of the steam mass flow rate at the turbine outlet.
- Both methods can be used on any steam turbine.
- Steam turbine developed power depends on steam specific enthalpies, but the major impact on any steam turbine power has a steam mass flow rate (throughout the turbine and at each turbine extraction).

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