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AN OVERVIEW OF THE EXPLOITATION OF STEAM IN THE SECONDARY SYSTEMS OF NPP KRŠKO

PREGLED SISTEMOV ZA ODJEM PARE V SEKUNDARNEM KROGU NEK

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Keywords: nuclear power plant, steam exploitation, thermodynamic analysis, district heating

Abstract

Nuclear energy is used to produce electricity; it can also be applied in a cogeneration process to produce power and heat. Nuclear energy is a very clean source as it produces almost no greenhouse gases, such as CO_2. Under the Kyoto Protocol, the signatory countries committed themselves to reducing CO_2 emissions; therefore, it is reasonable to take advantage of existing nuclear facilities to the greatest extent possible. This means that even though they were built only to produce electricity (Krško NPP, for example), they can also be used for other applications: a source of heat for district heating or desalination of sea water in areas at risk of a lack of drinking water. Nevertheless, the technology can be upgraded by using the experience of other nuclear power plants (NPPs) having similar district-heating systems.

In this paper, the focus was on models of steam consumption from the secondary system of the Krško NPP for the Krško and Brežice district-heating purposes. The Krško NPP has a Westinghouse PWR with 2,000 MWt and an electrical power output of 696 MW to the grid. The technological part is divided into three main systems: primary, secondary and tertiary. The first two are sealed and isolated from the environment while the third, which uses water from the River Sava for cooling, is connected to the outside environment. This paper focuses on the technical solution to obtain heat from the NPP's secondary system for district-heating purposes. According to thermodynamic calculations, the secondary system determines the reduction of produced electricity, when the

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steam is exploited in front of the turbine. This paper presents some technical, economic and safety solutions for the highly efficient extraction of vapour for district heating. Furthermore, some thermodynamic calculations and technical solutions for district-heating purposes using the Krško NPP for the Krško-Brežice area are shown.

Povzetek

Nuklearna energija se v svetu izkorišča za proizvodnjo električne energije, kot tudi za kogeneracijo – torej proizvodnjo električne energije in toplote. Velja za čisti vir energije, saj v procesu ne nastajajo toplogredni plini, predvsem CO_2. Po Kjotskem protokolu so države podpisnice zavezane k zmanjšanju izpustov CO_2, torej bi bilo smiselno obstoječe jedrske objekte izkoristiti v največji mogoči meri. To pomeni, da bi jih tam, kjer so namenjeni samo za proizvodnjo električne energije (kot NEK), uporabili tudi za druge aplikacije, kot je izkoriščanje toplote v namen daljinskega ogrevanja ali razsoljevanja morske vode na območjih, kjer so velike možnosti za pomanjkanje oskrbe s pitno vodo. Pri tem si lahko pomagamo z izkušnjami iz ostalih nuklearnih elektrarn, ki že imajo podobne sisteme za kogeneracijo.

V našem primeru se bomo osredotočili na odjem pare iz sekundarnega kroga NEK za sistem daljinskega ogrevanja Krškega in Brežic. NEK ima Westinghouseov PWR z 2000 MWt in z močjo na pragu 696 MW. Tehnološki del je razdeljen na primarni, sekundarni in terciarni krog, prva dva sta sklenjena in nimata stika z okoljem, tretji pa je povezan z okoljem, saj uporablja vodo iz Save za hlajenje. V članku je poudarek na tehnični rešitvi pridobivanja toplote iz sekundarnega kroga NEK za sistem daljinskega ogrevanja. Po termodinamične izračunu lahko določimo, koliko bi se zmanjšala proizvedena električna energija, saj bi paro odjemali pred turbino. V članku so predstavljene nekatere tehnične, ekonomske in varnostne rešitve za čim bolj učinkovito odjemanje pare za daljinsko ogrevanje. Nadalje so prikazani termodinamični izračuni in tehnične rešitve za sistem daljinskega ogrevanja s pomočjo NEK za območje Krškega in Brežic.

1 INTRODUCTION

This paper aims to present the reapplication of waste heat generated in electricity production at the Krško NPP. One of the reapplication options is the use of waste heat from the NPP for the heating of the towns of Krško and Brežice.

Heating plants, nuclear power plants, and thermoelectric power plants are industrial facilities generating not only inexpensive electrical energy but also very inexpensive steam. It is known that nuclear power plants produce electricity at considerably lower costs than heating and thermoelectric power plants. The indicators in terms of electric energy prices are even more favourable if nuclear energy is compared to other renewable sources of energy, such as photovoltaic power plants. Nuclear power is important for the production of very large amounts of cheap energy, both electricity and heat. In addition to its economic effects, nuclear energy also provides an option for the use of sustainable sources and the way towards a carbon-free society. Environmental problems such as rising levels of carbon dioxide in the atmosphere are deeply troubling issues. Nuclear power plant technology, including its safety, is constantly progressing and has achieved very high level. New types of reactors (fusion reactors) will allow an even more efficient use of nuclear fuel in the near and distant future. The efficiency of the use of nuclear reactors can be further improved by their upgrading for heating and cooling purposes.

District heating and cooling is one of the possible solutions for optimising the operations of nuclear power plants. Examples of good practice are the nuclear power plants Bilibino in Russia and Beznau in Switzerland. In this article, we will attempt to find technical solutions and economic analysis for the PWR nuclear power plant in Krško.

2 KRŠKO NPP

The Krško NPP is a Westinghouse PWR plant with a power rating of 2,000 MWt, a net electrical output of up to 696 MWe and is connected to the 400 kV grid. It generates more than 5 TWh of electrical energy per year or over 40% of the electricity produced in Slovenia, [1]. The Krško NPP's major components are illustrated in Figure 1.

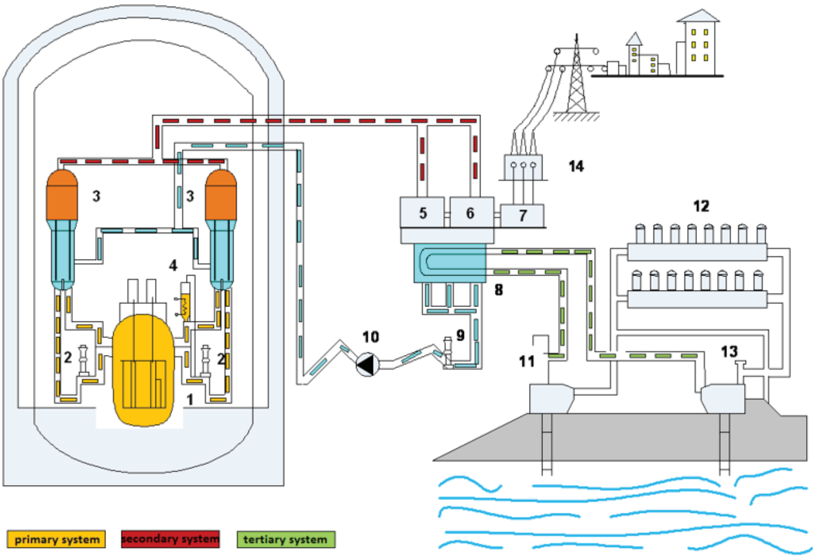

Figure 1: *NPP operating diagram [1]*

Key:

1 Reactor
2 Reactor coolant pumps
3 Steam generators
4 Pressurizer
5 High-pressure turbine
6 Low-pressure turbines
7 Electric generator
8 Condenser
9 Condensate pump
10 Feedwater pump
11 Cooling Sava River water pump
12 Cooling towers with cells
13 Cooling tower pump
14 Transformer

2.1 Description of the Secondary Systems in Krško NPP

This paper focuses on the NPP's secondary system that, in terms of thermodynamics, acts as a heat engine, similar to a conventional thermoelectric power plant.

Dry saturated steam generated in the steam generators enters the high-pressure turbine, where it expands to 9 bar, thus creating force. After expansion, steam becomes wet and it flows into the moisture separator and reheater where water drops are removed; saturated steam still remains to be reheated in reheaters. Such reheated steam expands in low-pressure turbines to a condenser pressure of 0.05 bar. The steam is condensed in the condenser and the condensate water is pumped by the condensate pumps to the main feedwater pumps returning the water to the steam generators, [2]. Figure 2 shows a simplified diagram of the secondary system.

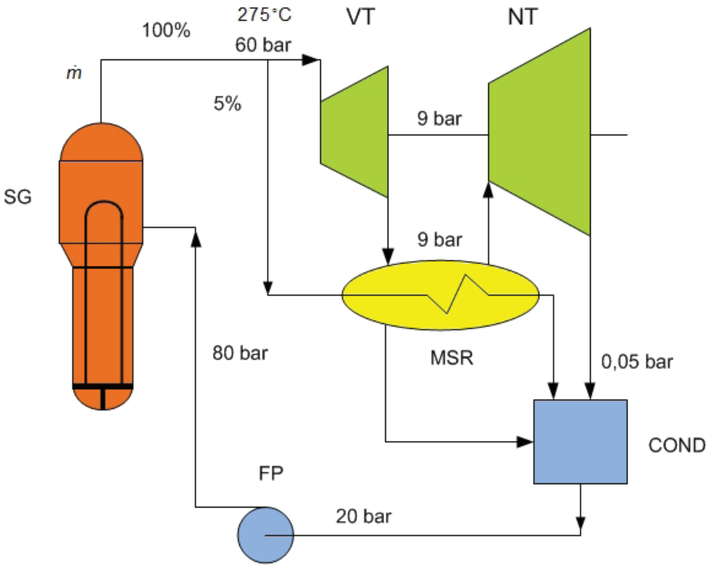

Figure 2: *Simplified diagram of the Krško NPP's secondary system*

Key to symbols used in Figure 2: SG – steam generator, VT ('HP') – high-pressure turbine, NT ('LP') – low-pressure turbine, MSR – moisture separator and reheater, COND – condenser, FP – feedwater pump.

Each element will be computed separately, i.e. VT (HP), followed by MSR, NT (LP) and finally FP. What happens to the enthalpy in each element will be determined, and the power output of the low-pressure turbine needed for any further computation purposes will be computed. A Mollier diagram and thermodynamic equations will be used, [2].

3 CALCULATION OF ENTHALPY FLOWS AND LOW-PRESSURE TURBINE POWER OUTPUT IN KRŠKO NPP

3.1 Introduction

The first law of thermodynamics will be used for the computation. Technical problems will be focussed on, as they are most relevant here; therefore, we begin with the following Equation (3.1):

$$\dot{Q}_{12} - \dot{W}_{12} = \dot{m}(h_2 - h_1) \tag{3.1}$$

In an adiabatic process Q = 0, and Equation (3.2) is developed to be used in the calculation.

$$(\dot{W}_{t12})_{ad} = \dot{m}(h_1 - h_2) \tag{3.2}$$

The data used for the calculation is taken from the Krško NPP's internal documents, [3].

3.2 Calculation of enthalpy flows and power outputs

3.2.1 High-pressure turbine

The processes in the high-pressure turbine in a Mollier diagram are illustrated in Figure 3.

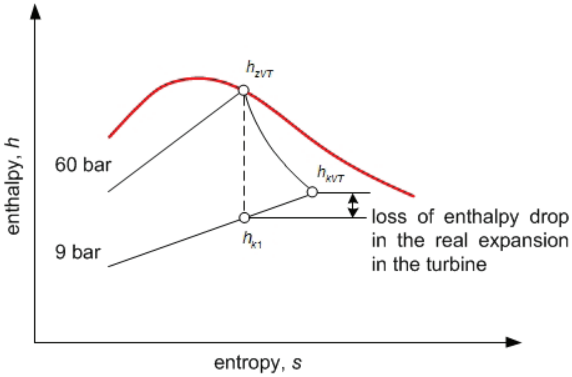

Figure 3: *Expansion in a high-pressure turbine in an h-s diagram*

The mass flow rate into the high-pressure turbine accounts for 95% of the total mass flow, which is why 0.95 is added to the right side of Equation (3.2) to calculate the turbine power output. The mass flow rate determined from the data is $\dot{m} = 1{,}088\,\frac{\text{kg}}{\text{s}}$. Furthermore, it is also taken into account that the expansion in the turbine is not isentropic but with efficiency $\eta_{VT} = 0.7879$. The unknown values are taken from the mechanical engineering handbook or a similar handbook, whereas the remaining values are calculated. Finally, the turbine power output is obtained using Equation (3.2):

$$\dot{W}_t = 0.95 \cdot 1{,}088 \cdot (2{,}785 - 2{,}517) \doteq \underline{277\text{MW}}$$

3.2.2 MSR

The MSR removes drops from the steam and reheats the steam. Figure 4 shows the process, including the reheating, in an h-s diagram. No turbine efficiencies are taken into account in the figure.

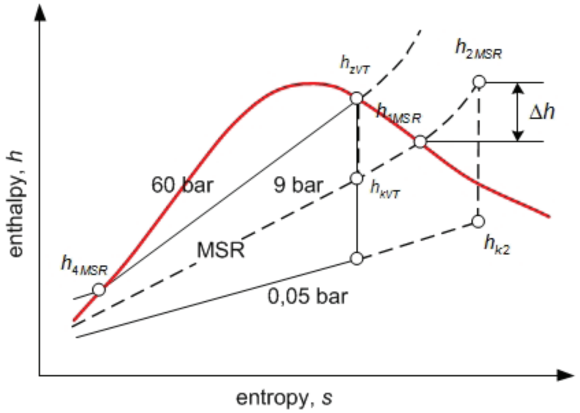

Figure 4: *Process including steam reheating in an h-s diagram*

First, the mass flow rates of steam and drops are calculated $903.4\frac{\text{kg}}{\text{s}}$, and $903.4\frac{\text{kg}}{\text{s}}$, respectively, and total mass flow $1{,}033.6\frac{\text{kg}}{\text{s}}$. From an energy balance in Equation (3.3), enthalpy growth Δh can be calculated using Equation (3.4), whereas other values are taken from the previous calculation or found in a mechanical engineering handbook, by taking into consideration the fact that the mass flow rate of fresh steam taken in front of the turbine accounts for 5% of the total mass flow rate. The basis for the overall calculation is the Mollier diagram for MSR shown in Figure 4. The value we are interested in is the initial state of steam at the entrance to the low-pressure turbine to be obtained from Equation (3.5).

$$x_{kVT} \cdot m_{VT} \cdot (h_{2MSR} - h_{1MSR}) = m_p \cdot (h_{zVT} - h_{4MSR}) \tag{3.3}$$

$$\Delta h = (h_{2MSR} - h_{1MSR}) = \frac{\dot{m}_p \cdot (h_{zVT} - h_{4MSR})}{x_{kVT} \cdot \dot{m}_{VT}} \tag{3.4}$$

$$h_{zNT} = h_{2MSR} = h_{1MSR} + \Delta h = 2{,}772 + 94.8 = 2{,}867\frac{\text{kJ}}{\text{kg}} \tag{3.5}$$

3.2.3 Low-pressure turbine

The calculation for the low-pressure turbine is the same as with the high-pressure turbine, but with different data. Figure 5 illustrates the processes in the turbine.

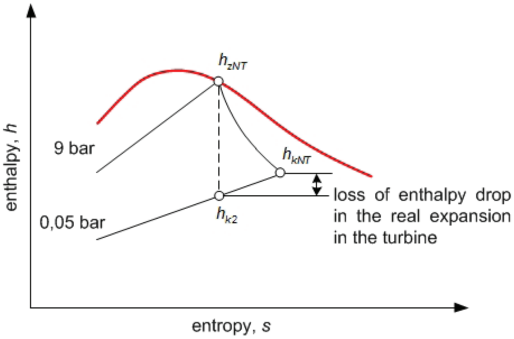

Figure 5: *Expansion in a low-pressure turbine in an h-s diagram*

Power output obtained in the calculation using Equation (3.6):

$$\dot{W}_t = 0.874 \cdot 1{,}033.6 \cdot (2{,}867 - 2{,}246) \doteq \underline{561\mathrm{MW}} \tag{3.6}$$

3.2.4 Feedwater pump

Equation (3.7) is used to calculate the feedwater pump output, whereas the other data is available in Figure 2 or found using a mechanical engineering handbook. The actual feedwater pump output, taking into consideration a 50% efficiency, is shown in Equation (3.8).

$$\dot{W}_{FP1} = \dot{m}(p_1 - p_2) \cdot v \tag{3.7}$$

$$\dot{W}_{FP} = \frac{\dot{W}_{FP1}}{\eta_{FP}} = \frac{-7.7}{0.5} \doteq \underline{-15.4\mathrm{MW}} \tag{3.8}$$

3.3 Computed values

Certain data from this section will also be used in the next one to see how much the power plant output (low-pressure turbine power output) would be lower, if the steam is used for district heating. The values indicated in this section are summarised in Table 1, [2].

Table 1: *Computed values*

	Designation (unit)	Value
High-pressure turbine power output	$\dot{W}_t$ (MW)	277
Quality of steam from high-pressure turbine	x_{kVT}	0.874
Low-pressure turbine power output	$\dot{W}_t$ (MW)	561
Quality of steam from low-pressure turbine	x_{kNT}	0.87
Feedwater pump output	$\dot{W}_{FP}$ (MW)	–15.4

4 EXTRACTION OF STEAM FOR KRŠKO AND BREŽICE DISTRICT-HEATING PURPOSES

4.1 Introduction

A heat exchanger would be installed behind the MSR and in front of the low-pressure turbine. Otherwise, all inlet and outlet flow rates should be calculated again, requiring a very expensive process, i.e. a new design of the system. Steam extraction in front of the low-pressure turbine is also the most cost effective. Another reason for steam extraction here is the relatively high level of steam temperature needed for district heating (at least 100° C). Figure 6 shows the heat exchanger location.

In order to meet the Krško and Brežice district-heating requirements, 80 MW of heat is needed. A calculation will be made for the amount of low-pressure turbine power output reduction in the case of a 10%, 20% or 30% heat loss. The results thus obtained will provide a basis for the comparison of heat and electricity prices.

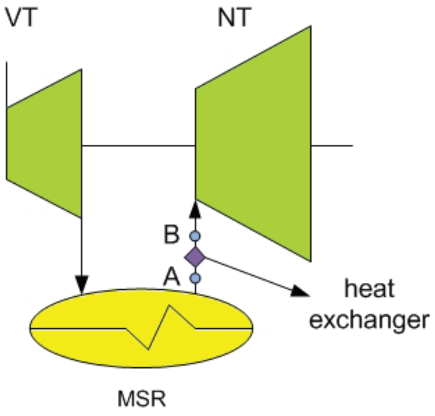

Figure 6: *Location of steam extraction or heat exchanger*

4.2 Calculation

As a result of steam extraction, enthalpy changes at the entrance to the low-pressure turbine, i.e. enthalpy in point B (Figure 6). This is the only parameter subject to change. It is to be calculated for each case separately (i.e. at various values of losses) using Equation (4.1).

$$\dot{Q} = \dot{m}_{NT} \cdot (h_A - h_B) \tag{4.1}$$

4.2.1 10 % loss

In this case, the required heat is $\dot{Q}_1 = 1.1 \cdot 80 = 88\text{MW}$, then, by using (4.1) we calculate h_B. This value is then put into Equation (4.2) and the turbine new power output is computed using Equation (4.3) and by how much the turbine power output has decreased, using Equation (4.4).

$$h_{kNT} = h_B - \eta_{NT} \cdot (h_B - h_{k2}) \tag{4.2}$$

$$\dot{W}_{t1} = 0.874 \cdot 1{,}033.6 \cdot (2{,}770 - 2{,}225) \doteq 492\text{MW} \tag{4.3}$$

$$\Delta P_1 = \dot{W}_t - \dot{W}_{t1} = 561 - 492 = 69\text{MW} \tag{4.4}$$

4.2.2 20 % loss

The calculation made is similar to the one above, yet with different values. The turbine power output is shown in Equation (4.5) as well as by how much the turbine power output has decreased in Equation (4.6).

$$Q_2 = 1.2 \cdot 80 = 96\text{MW}$$

$$\dot{W}_{t2} = 0.874 \cdot 1{,}033.6 \cdot (2{,}761 - 2{,}223) \doteq 486\text{MW} \tag{4.5}$$

$$\Delta P_2 = \dot{W}_t - \dot{W}_{t2} = 561 - 486 = \underline{75\text{MW}} \tag{4.6}$$

4.2.3 30 % loss

The turbine power output is now in Equation (4.7) as well as by how much the turbine power output has decreased in Equation (4.8).

$$\dot{Q}_3 = 1.3 \cdot 80 = 104\text{MW}$$

$$\dot{W}_{t3} = 0.874 \cdot 1{,}033.6 \cdot (2{,}752 - 2{,}221) \doteq 480\text{MW} \tag{4.7}$$

$$\Delta P_3 = \dot{W}_t - \dot{W}_{t3} = 561 - 480 = \underline{81\text{MW}} \tag{4.8}$$

Figure 7 shows the ratio between the power plant output and the quantity of steam in the case of different values of losses in the district-heating system.

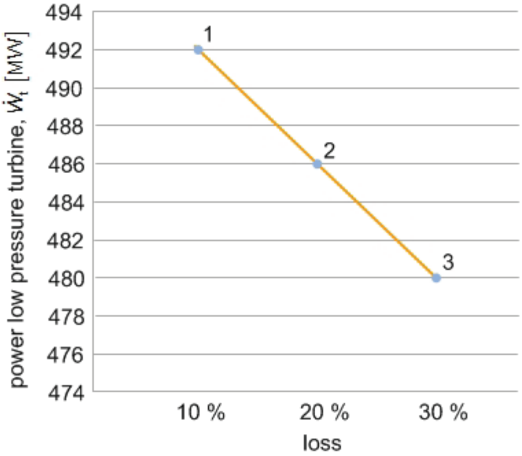

Figure 7: *Ratio between low-pressure turbine power output and the quantity of steam in the case of different values of losses in the district-heating system*

4.3 Computed values and comments

For each case separately, the minimum cost of 1 MWh of heat to compensate the cost of electricity from the NPP, which is €30 per 1 MWh, will be calculated, based on the assumption of a 24 h operation. The values are indicated in Table 2, [2].

Table 2: *Computed values*

No.	Losses in district heating (%)	Low-pressure turbine power output (MW)	Heat price (€/MWh)
1	10	492	25.9
2	20	486	28.1
3	30	480	30.4

The calculations showed that in view of the assumed heat losses, the price of 1 MWh of heat varies between € 25/MWh and € 31/MWh. This price can hardly be compared to the market prices, since many factors should have been taken into consideration, such as investment, amortisation period, CO_2 taxes, and others. No investment in the NPP was taken into consideration in the computation nor any investment in the distribution, nor any subsidies as there are no CO_2 emissions. However, the comparison was made of the price of 1 MWh of electricity and 1 MWh of heat. It is not surprising that interest in combined heat and power (CHP) technologies is growing.

5 CONCLUSION

This paper deals with the use of waste heat from the NPP for Krško and Brežice district-heating purposes. This would result in an increased efficiency of the existing electric power facility. There is a great deal of heat wasted in the Krško NPP and it should be used in order to increase the efficiency of the plant. A district-heating system would contribute to a cleaner environment in the Krško and Brežice area and would provide a more reliable heat supply. Moreover, it would also provide a financially more favourable solution. This paper also presents an original concept and a computation of the indicative costs of the generated heat.

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Nomenclature

NEK	Nuklearna elektrarna Krško
NPP	nuclear power plant
$\dot{Q}$	heat flow rate [J/s]
$\dot{W}$	power output [W]
$\dot{m}$	mass flow rate [kg/s]
h	specific enthalpy [J/kg]
η	efficiency
MSR	moisture separator and reheater
x	quality of steam
P	power [W]
CHP	power and heat cogeneration