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THERMAL AND HYDRAULIC CALCULATION OF A DELTA 125 STEAM GENERATOR FOR A POWER UNIT WITH AN AP1000 REACTOR

М. Галацан, І. Салагор. **Теплогідравлічний розрахунок парогенератору типу Delta 125 для енергоблоку з реактором АР1000.** Енергоблоки АР1000 мають великі переваги перед популярними в Україні енергоблоками з реакторами типу ВВЕР-1000. Вони оснащені пасивними системами безпеки, які дозволяють значно зменшити ризики техногенних аварій, навіть за умов екстремальних зовнішніх впливів. Крім того, їхня конструкція забезпечує значну економію ресурсів під час будівництва та експлуатації. Впровадження реакторів АР1000 є не лише кроком до відновлення енергетичного потенціалу країни, але й стратегічною інвестицією у майбутнє. У цьому контексті теплогідравлічний розрахунок парогенератора Delta 125, який є ключовим компонентом енергоблока АР1000, є надзвичайно актуальним і важливим для обґрунтування доцільності використання таких установок в умовах української енергосистеми. Проведено порівняльний аналіз вертикальних та горизонтальних парогенераторів. Описано парогенератор Delta 125 та його принципову теплову схему. Виконано теплогідравлічний розрахунок: визначено теплову потужність економайзерної та випарної ділянки, витрати теплоносія, побудовано (*t*-*Q*)-діаграму парогенератора, розраховано товщину стінок труб теплопередаючої поверхні та довжина труб, коефіцієнт теплопередачі, площа теплопередаючої поверхні економайзерної та випарної ділянки, масу труб парогенератора, визначено гідравлічний опір першого та другого контурів, достатність парового простору для сепарації пари, жалюзійний сепаратор, розміри та маса основних вузлів корпусу. Розраховано вартість парогенератора, розрахункові витрати та залежність приведених витрат від швидкості теплоносія.
Ключові слова: розрахунок парогенератора Delta 125, АЕС з АР1000

M. Galatsan, I. Salahor **Thermal and hydraulic calculation of a Delta 125 steam generator for a power unit with an AP1000 reactor**. AP1000 power units have great advantages over VVER-1000 power units which are popular in Ukraine. They are equipped with passive safety systems that significantly reduce the risks of man-made accidents, even under conditions of extreme external influences. In addition, their design provides significant resource savings during construction and operation. The introduction of AP1000 reactors is not only a step towards restoring the country's energy potential, but also a strategic investment in the future. In this context, the thermal-hydraulic calculation of the Delta 125 steam generator, which is a key component of the AP1000 power unit, is extremely relevant and important to justify the feasibility of using such units in the Ukrainian power system. A comparative analysis of vertical and horizontal steam generators is carried out. The Delta 125 steam generator and its basic thermal scheme are described. The following thermal-hydraulic calculation was performed: the heat output of the economizer and evaporator sections, the coolant flow rate, the (*t*-*Q*)-diagram of the steam generator, the thickness of the walls of the heat transfer surface pipes and the length of the evaporator section pipes, and the heat transfer coefficient were calculated, the heat transfer surface area of the economizer and evaporator sections, the length and weight of the steam generator pipes, the hydraulic resistance of the first and second circuits, the sufficiency of the steam space for steam separation, the louver separator, the dimensions and weight of the main components of the body were determined. The cost of the steam generator, the estimated costs, and the dependence of the reduced costs on the coolant velocity were calculated.
Keywords: spindle, calculation of the Delta 125 steam generator, NPP with AP1000

Introduction

The brutal war in Ukraine has resulted in significant losses in the energy sector, creating numerous and extremely complex challenges for the country's overall energy stability. Intense combat operations have damaged or even completely destroyed a number of thermal power plants [1], leading to a serious reduction in electricity generation and affecting the operation of industrial enterprises, residential complexes, and critical infrastructure facilities. Moreover, the strategically important location and control of the Zaporizhzhia Nuclear Power Plant (ZNPP), the largest nuclear facility in Ukraine [2], further complicate the situation by introducing a range of technical, safety, and political challenges related to ensuring uninterrupted energy supply.

In this context, where energy security issues have become particularly pressing, the government and the country's leading experts are focusing their efforts on restoring Ukraine's energy potential and strengthening its energy independence. One of the key strategic directions is the development and implementation of modern technologies that will not only restore the lost capacity but also ensure a high level of reliability and efficiency in the future. Among such innovative projects is the construction of new power units at the Khmelnytskyi Nuclear Power Plant, including fourth-generation reactors based on Westinghouse technology of the AP1000 type [3].

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It is important to note that the implementation of this project is accompanied by extensive research and engineering work, among which the thermal-hydraulic calculation of the Delta 125 steam generator occupies a special place. This calculation is critically important for the AP1000 power unit, as it provides accurate modeling of heat exchange, enables the optimization of system performance, and guarantees the safe operation of the power unit under complex operating conditions. Through the implementation of such advanced technologies and systems, Ukraine has every opportunity not only to restore its energy capacities but also to make a significant contribution to ensuring the country's energy independence and sustainable development in the long term.

Analysis of recent publications and problem statement

An analysis of the available literature shows that modern research in the field of thermal hydraulics is focused on detailing the operation of various steam generators [4]. However, despite the large number of scientific papers on this topic, publicly available information on the design features and operational characteristics of the Delta 125 steam generator is extremely limited. This is due both to commercial confidentiality and to the specific technological solutions used in the development of this equipment.

This lack of information creates significant difficulties in conducting a comprehensive analysis and calculation of thermal-hydraulic processes, as building a reliable mathematical model requires access to all key parameters and design solutions. Given the prospects for deploying this type of steam generator in Ukraine [5] at new nuclear power plants, this work has special scientific and practical value. It will not only allow for a deeper understanding of the principles of the steam generator's operation but also contribute to the development of effective computational models for assessing its thermal and hydraulic characteristics, as well as for estimating its cost.

Thus, the relevance of this research is underscored by the need to fill the information gap that exists in open sources and to ensure the safe and economically efficient operation of new-generation nuclear facilities.

The aim of this work is to perform a thermal-hydraulic calculation of the Delta 125 steam generator for a nuclear power plant with an AP1000 reactor and to compare vertical and horizontal steam generators.

To achieve this aim, the following tasks are set:

– to analyze vertical and horizontal steam generators;
– to perform a thermal calculation;
– to perform a hydraulic calculation;
– to calculate the cost of the steam generator;
– to compare the efficiency of the heat exchange surface of vertical and horizontal steam generators.

Comparative analysis of vertical and horizontal steam generators

There are two main types of steam generators – vertical and horizontal [6] – that have been in operation for over 50 years. During this extended period, a vast amount of practical experience has been accumulated, which has made it possible to identify a number of problems, drawbacks, and characteristic features of each of these types. This, in turn, has led to continuous improvement and modernization of design solutions.

Horizontal steam generators have several advantages over vertical ones that enhance the operational efficiency and safety of the plant. Among these advantages are the following [7, 8]:

1) moderate steam load, which is usually lower than that of vertical steam generators. this allows for steam separation to be achieved solely by gravity and the use of a baffle-type separator, which ensures effective separation of water droplets from the steam;

2) availability of a sufficient reserve of water in the secondary circuit. this reserve is extremely important in emergency situations, such as a loss of feedwater to the reactor, as it allows for rapid cooling of the reactor and prevents overheating;

3) stepwise evaporation method, which helps maintain normal – that is, permissible – concentrations of substances in critical areas of the unit. this helps prevent corrosive effects, as the evaporation process is continuously adjusted to ensure optimal distribution of the coolant;

4) horizontal arrangement of the heat exchange surface (Fig. 1), which ensures reliable natural circulation. this arrangement promotes uniform temperature distribution inside the unit, positively affecting the efficiency of the heat transfer process;

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5) reduced scheduled maintenance requirements due to design solutions that allow for easy disconnection of the collectors from the circulation pipeline. this makes it possible to carry out repair work on several steam generators simultaneously, which contributes to an increased capacity utilization factor and ensures continuous reactor operation.

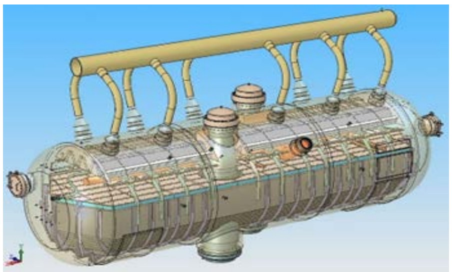

Fig. 1. Horizontal steam generator PGV-1000 of the WWER-1000 reactor

Vertical steam generators also exhibit a number of significant advantages that allow them to compete with their horizontal counterparts, thanks to their long history of use and the evolution of design solutions over the past fifty years.

Vertical steam generators, such as the Delta 125 model, have a number of unique characteristics that contribute to their efficiency:

1. Vertical steam generators are characterized by significantly lower construction costs and occupy considerably less space. According to comparative data, horizontal steam generators used at modern nuclear power plants with VVER-type reactors occupy, on average, an area four times greater than that required to accommodate two delta 125 steam generators at an AP1000 plant, while demonstrating higher specific capacity [9]. This fact indicates the economic feasibility of using vertical designs, which reduce both capital expenditures and the space requirements for installation. the design features of the vertical steam generator's shell also offer advantages: the wall thickness in these models is, on average, 1.7 times less than that of steam generators used in vver reactors [10]. Reducing wall thickness not only lowers the overall weight of the structure but also positively impacts the cost-effectiveness of production and operation, which is an important factor in the development of new models;

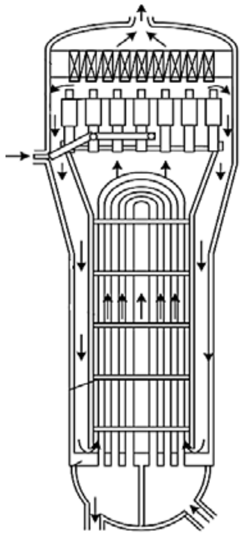

Fig. 2. Example of heat exchange tubes in vertical steam generators Delta 125

2. Vertical steam generators are characterized by significantly longer heat transfer tubes. According to the data, the difference is approximately 20 meters for vertical models (Fig. 2), compared to 12.5 meters for horizontal models. this increases the heat exchange surface area [10];

3. One of the key advantages of vertical steam generators is the absence of stagnant zones in the working space. In the design of such steam generators, these zones are virtually nonexistent, which eliminates the risk of local accumulation of coolant or steam. in comparison, horizontal steam generators typically have stagnant zones located near the bottom nozzles, which can affect the uniformity of heat transfer and reduce the overall efficiency of the unit [9];

4. A two-stage separation system is used, which achieves a higher degree of steam drying than in horizontal steam generators [9];

5. The design of the vertical steam generator allows for preheating and thus an increased average temperature differential in the system, which is crucial for achieving high steam parameters – that is, the steam generator pressure can be increased by 0.4 MPa. Such zoning in vertical steam generators is unique because horizontal counterparts cannot effectively separate the single-phase zone, which limits their performance [11].

Vertical steam generators show great promise in the development of nuclear energy thanks to their advantages: thermal efficiency, compactness, and the ability to operate at elevated steam parameters.

At the same time, horizontal steam generators remain a reliable choice for traditional nuclear power plants, especially in conditions where ease of maintenance, reliability in crisis situations, and time-tested technical solutions play a key role.

Analysis of the heat transfer surface efficiency of vertical and horizontal steam generators

The efficiency of the heat transfer surface is an extremely important indicator that determines not only the performance of thermal power systems but also affects the overall economic benefit of their use. This indicator is influenced by many factors, such as the number of tubes, their material, heat transfer surface area, tube diameter, tube length, and others.

As seen from the information in Table 1, vertical steam generators are characterized by significantly longer tubes than horizontal ones – the tube length in vertical steam generators is almost twice that of horizontal ones. This aspect contributes to greater contact between the coolant and the tube surface.

Table 1

Parameters of the heat transfer surface of the two steam generators PGV-1000 and Delta 125

Parameter/Steam Generator Name	PGV-1000 × 2	Delta 125	
	Project [9]	Project	Estimated
Thermal Power, MW	1500	1707.5	1707.5
Number of Tubes	22000	10025	10233
Heat transfer surface area, m²	12230	11477	10936.06
Tube Material	08X18H10T	Inconel 690-TT	
Tube Diameter, mm	16	17.5	
Average tube length, m	11.1	20.823	20.63

The heat transfer surface area directly depends on a number of characteristics and design parameters of the steam generator, which together create optimal conditions for efficient heat exchange. It should be noted that every detail – from the arrangement of the tubes to their geometric parameters – plays a decisive role in shaping the overall efficiency of the steam generator.

One of the key factors affecting heat transfer is the method of tube arrangement in the steam generator, since it determines not only the surface area available for heat exchange but also the hydraulic resistance that occurs when the coolant flows inside the system. In vertical steam generators, the tubes are installed vertically, which ensures optimal and natural separation of the water and steam phases. Such vertical separation ensures a more uniform and efficient contact between the coolant and the tube surface, which, in turn, improves the heat transfer process.

On the other hand, in horizontal steam generators, the design features of tube arrangement often create additional challenges. Due to the horizontal arrangement of the tubes, a phenomenon often referred to as “steam plugs” may occur. These plugs impede the normal flow of the working fluid, reduce the efficiency of heat transfer, and increase the hydraulic resistance, negatively affecting the overall performance of the steam generator. Thus, while horizontal steam generators demonstrate certain advantages in other design aspects, these features of tube arrangement create additional challenges for maximizing the efficiency of the heat transfer surface.

If we focus exclusively on the number of tubes and the heat transfer surface area, it can be noted that two horizontal PGV-1000 steam generators have 22000 tubes, which together provide a heat transfer surface area of 12230 m². In comparison, the vertical Delta 125 steam generator has 10233 tubes, but here the heat transfer surface area is 11477 m². Based on these data, one can determine the efficiency of the heat transfer surface. The results of this calculation are presented in Table 2.

Table 2

Efficiency of the heat transfer surface

Parameter	PGV-1000 × 2 [9]	Delta 125
Heat power, MW	1500	1707.5
Heat transfer surface area, m²	12230	10936.06
Specific heat power of heat transfer surface (efficiency MW/m²)	0.1226	0.1561 (+27%)

Vertical steam generators have a 27% higher heat exchange surface efficiency during boiling on vertical tubes compared to horizontal steam generators. This is due to the higher heat transfer coefficient during boiling on vertical tubes. When comparing the PGV-1000 and the Delta 125, the heat transfer coefficient $\alpha''1$ is 34149 versus 38794 (W/m²×K), a difference of 13.6%, while the overall heat transfer coefficient k'' is 6053 versus 7660 (W/m²×K), a difference of 20.9%.

Calculation of the Delta 125 Steam Generator

The Delta 125 steam generator is a vertical steam generator (Fig. 3). The core of its design consists of U-shaped tubes made from high-grade nickel-chromium-iron alloy Inconel 690-TT, which provides excellent resistance to corrosion and high-temperature stress. The tubes are arranged in a tri-

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angular pitch, which promotes uniform heat distribution and reduces local overheating. This, in turn, ensures enhanced heat transfer efficiency and operational stability of the steam generator.

The unit is equipped with built-in moisture separation equipment, specifically a two-stage moisture separation system that ensures a higher degree of steam drying.

It should be noted that detailed technical specifications and parameters of the Delta 125 steam generator are classified as confidential information, and therefore not all data is publicly available.

Input and Approximate Data Typical for the Operating Characteristics of the Delta 125 Vertical Steam Generator:

– Steam output of the steam generator: $D = 944$ kg/s;

– Coolant parameters: $P_1 = 15.513$ MPa; $t_1' = 324.7$ °C; $t_1'' = 279.4$ °C;

– Steam parameters: $P_2 = 5.76$ MPa; $t_2' = t_s = 272.8$ °C;

– Feedwater temperature: $t_{feed} = 226.7$ °C;

– Circulation ratio: $K_c = 3.7$ [3].

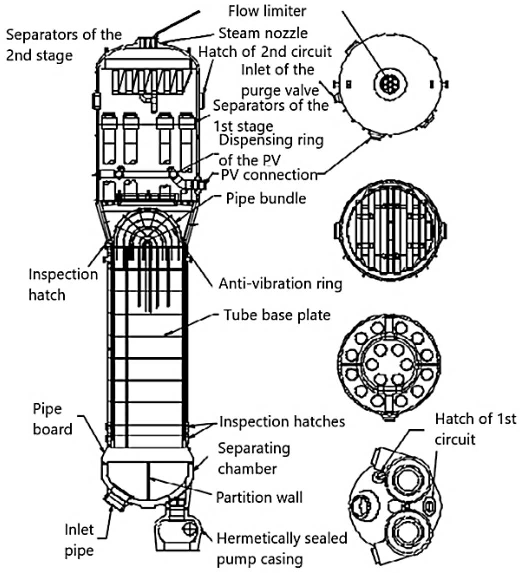

Fig. 3. Vertical Steam Generator Delta 125 of the AP1000 Reactor

To initiate the thermal calculation of the steam generator, the thermal power of the economizer and evaporator zones was determined–this being one of the key stages in analyzing the performance of thermal equipment.

During the determination of thermal power, the main thermodynamic parameters were used, particularly enthalpies obtained from the properties of water and steam [12]. The parameters identified include the enthalpy of saturated steam, feedwater, specific steam generation, and the enthalpies at the inlet and outlet of the coolant from the steam generator.

The next stage of the calculation involved determining the coolant flow rate using the thermal balance equation of the steam generator. This calculation allows for the determination of the amount of coolant required to ensure the specified thermal power. Based on the obtained data, a (t-Q)-diagram of the steam generator was constructed, illustrating the dependence of the temperature regime on the thermal load.

This diagram is shown in Fig. 4.

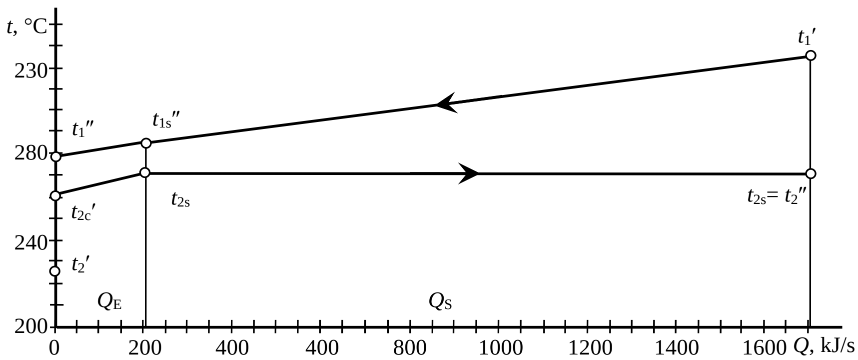

Fig. 4. t–Q diagram of the steam generator

The heat exchange tubes are made of Inconel 690 alloy steel, while the shell elements are made of carbon steel.

The next step involved determining the heat exchange surface area and the length of the tubes in the evaporator section. At a selected coolant velocity of 5.25 m/s (the actual and optimal velocity), the thermophysical properties of water at t_1' and P_1 were determined, as well as the thermal resistance of heat transfer, which is a critical parameter for analyzing heat exchange efficiency within the steam generator. The specific heat flux – a key indicator of heat transfer intensity – was also calculated.

Additionally, the heat transfer coefficient was determined using the formula for longitudinal flow, which enables the assessment of heat exchange efficiency in the system, and the length of the heat exchange tubes was calculated.

The calculation results showed that the heat exchange surface area is 10936.06 m². Moreover, the total length of the steam generator tubes reached 366704 meters, and the length of a single tube was established at 20.63 meters. Finally, the total tube mass was calculated to be 128 tonnes.

The hydraulic calculation begins with a series of calculations related to the hydraulic resistances of both the first and the second circuits. For this, the input data were used, including the coolant density values: $\rho_{1in}' = 655.11$ kg/m^3 at temperature $t_1' = 324.7$ °C, $\rho_{1out}'' = 751.34$ kg/m³ at temperature $t_1'' = 279.4$ °C, as well as the average value $\rho_{1avg} = 707.89$ kg/m³, obtained at the average steam generator temperature $t_{1avg} = 302.05$ °C.

These data were supplemented with information on the absolute roughness of the Inconel 690 surface, which was assumed to be $k = 0.01$ mm, and the operating pressure, which was $P_1 = 15.513$ MPa.

The calculation determined the pressure losses in the primary circuit coolant loop, which amounted to 63463 Pa, as well as in the working medium circuit, where the pressure losses reached 217824 Pa.

In addition, the calculation included determining the evaporation mirror surface area, which amounted to 21.763 m².

The final stage of this calculation was determining the mass of individual parts of the steam generator. During the work, calculations were carried out for various structural elements, in particular, the mass of the upper shell was determined to be 166.5 tonnes, and the mass of the lower shell – 133.7 tonnes.

In addition, the mass of the upper elliptical vessel head was calculated to be 3.7 tonnes, and the mass of the lower elliptical vessel bottom – 3.2 tonnes. To this dataset was added the calculation of the mass of other parts of the steam generator, which amounted to 262.7 tonnes.

Further calculations made it possible to determine the cost of each group of components based on their mass indicators. As a result, it was established that the cost of the vessel amounts to 173 million USD, the tube bundle – 50 million USD, and other parts of the steam generator are estimated at 146 million USD. According to our calculations, the cost of the steam generator is 369 million USD.

Conclusions

The thermal-hydraulic calculation of the Delta 125 steam generator has been completed, and the calculated data coincide with the actual design characteristics of the steam generator with an error of no more than 4.95%.

The advantages and disadvantages of vertical and horizontal steam generators have been analyzed. In comparison, it was determined that vertical SGs have a 27% higher specific heat exchange surface power. This is explained by a 13.6% higher heat transfer coefficient during boiling on vertical tubes than on horizontal ones, and a 20.9% higher overall heat transfer coefficient.

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