ГЛОБАЛЬНАЯ ЯДЕРНАЯ БЕЗОПАСНОСТЬ, 2019 №3(32), С. 74–79

ЭКСПЛУАТАЦИЯ ОБЪЕКТОВ АТОМНОЙ ОТРАСЛИ

УДК 621.181

СРАВНИТЕЛЬНЫЙ АНАЛИЗ ПАРОГЕНЕРИРУЮЩЕГО ТРАКТА В ГОРИЗОНТАЛЬНЫХ ПАРОГЕНЕРАТОРАХ АЭС

© 2019 М.Н.С. Ансах (Гана)[*], Н.Н. Подрезов[**]

[*]*Томский политехнический университет, Томск, Россия*

[**]*Волгодонский инженерно-технический институт – филиал Национального исследовательского ядерного университета «МИФИ», Волгодонск, Ростовская обл., Россия*

В статье дан краткий обзор влияния различных схем сепарации в горизонтальных парогенераторах (ПГВ) АЭС на качество пара, производимого в паровом тракте для подачи в турбину. Дальнейший рост тепловой мощности ПГВ без существенного увеличения габаритных размеров определяется «удержанием» сепарационной характеристики ПГВ в пределах, заданных сухостью отбираемого пара. В этом направлении ключевыми оптимизациями горизонтальных ПГВ следует считать отказ от жалюзийных сепараторов в пользу пароприемных дырчатых листов с переменной перфорацией и разработку новой теплогидравлической схемы для двухпетлевого проекта ВВЭР-ТОИ.

Ключевые слова: парогенератор, сепарация пара, энергоблок ВВЭР, влажность пара, сепарация гравитационная, погруженный дырчатый лист, пароприемный дырчатый лист, технико-экономические показатели.

Поступила в редакцию 24.12.2018
После доработки 03.07.2019
Принята к публикации 05.07.2019

The SG is one of the main objects of increasing thermal power to increase steam production, the pressure of the generated steam and the electric power of the nuclear power plant accordingly. A distinctive feature of all existing and projected SG for WWER-based reactor installations is the horizontal layout of heat transfer U-shaped tubes connecting the «hot» and «cold» collectors of the heat exchanger. The second feature of horizontal SG is the use of gravity-precipitation separation for steam drying during single-movement coolant. There is always a large thermal irregularity due to low temperature pressures along the coolant moving between the collectors for all standard PGV structures of WWER reactor units. As a result, various thermal loads lead to the formation of «hot» and «cold» zones, which cause distortion of the level of the evaporation mirror, the vapor content and the vapor velocity.

These factors adversely affect the separation characteristics of PGV and, accordingly, on the quality of steam drawn to the turbine, limiting the steam capacity and thermal power SG. Until recently, it was believed that PGV-1000MKP or PGV-1000MKO horizontal steam generators reached near-limit thermal power at a level slightly above 800 MW, which, of course, is not enough to compete with vertical-type steam generators used in foreign projects. A further increase in the capacity of Russian SG is limited by the geometrical dimensions and possibilities of the thermal-hydraulic scheme of steam separation.

Potential customers have recently been paying increasing attention to comparative technical and economic indicators, the investment attractiveness of NPP projects, including Russian. When analyzing some modern foreign projects with water-cooled reactors, there is a tendency to a decrease in the number of loops of the reactor facility (RU) and an increase in

the unit power of the SG. These are the projects AP-1000 (Westinghouse), the Korean projects APR-1400 and APR + (KEPCO), EPR-1600 (AREVA) and some others.

Attention in this work is focused on a comparative analysis of the parameters of the thermal-hydraulic circuits of horizontal steam generators of different WWER projects from the point of view of increasing their steam production while observing the standards for the quality of separated steam supplied to the turbine.

The coolant having a pressure of the first circuit, passes through U-shaped coils, heats the feed water of the second circuit of the SG, which is under less pressure. The water around the tubes boils and the steam-water mixture enters under the perforated sheet, forming a steam pad. Wet vapor from the evaporation mirror above the perforated sheet moves upwards, losing moisture to the required conditions and then through separating devices (in old projects) or throttling (in new ones) enters the vapor receiving channel of the collector.

The criterion for the quality of the generated steam is the separation characteristic, which is the dependence of steam moisture on the height of the vapor volume and the speed of the steam from the evaporation mirror, figure 1.

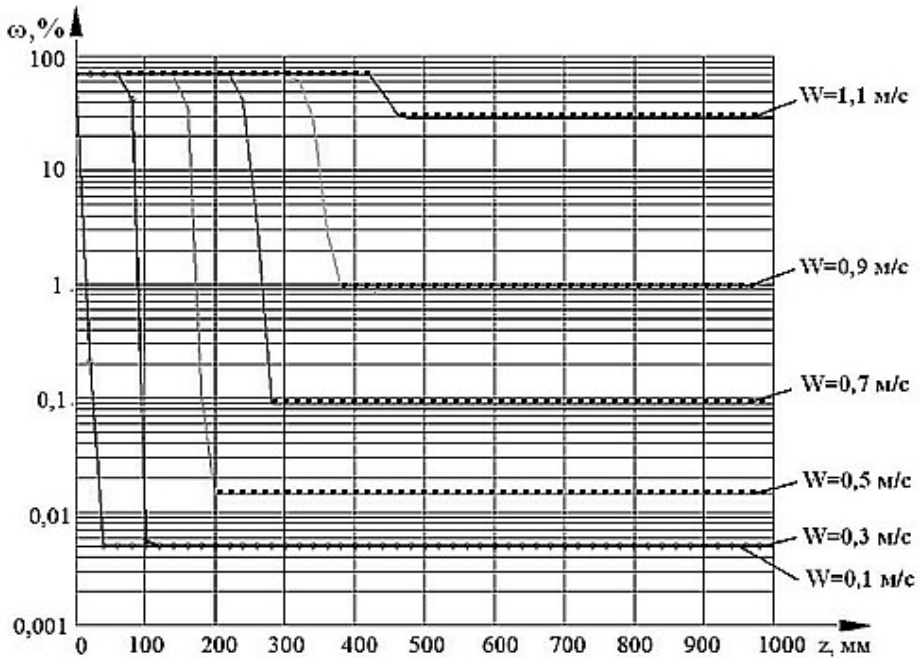

Figure 1 – Dependence of steam moisture (ω) in the area gravitational-precipitation separation the height of the vapor volume (z) and the speed (W) of movement of the steam [1]

From the analysis of Figure 1 it follows that the limiting speed of steam, at which gravitational-precipitation separation is possible, should be considered as 0,7 m/s. At higher steam speeds, the transported moisture loss exceeds the allowable 0,2%.

It should be noted that the improvement of the separation characteristics of the horizontal steam generators of the NPP did not happen immediately. Initially, as the main scheme was used with a louver separator, figure 2a. However, in the early 2000s, it became clear that more powerful NPP units required an increase in the reserve for steam production, the expansion of the allowable range of change in the level of the evaporation mirror.

At the same time was discovered the inefficient use of louver in SG with preliminary gravity separation above the bubble layer in conditions of natural convection two-phase working medium [2]. Then it actually turned away from two-step steam separation in favor of a single-stage by replacing the louver on the perforated shield plate, figure 2b. Louver separators are used only in WWER-440 while in WWER-1000 and 1200 they are all replaced by a ceiling plate shields.

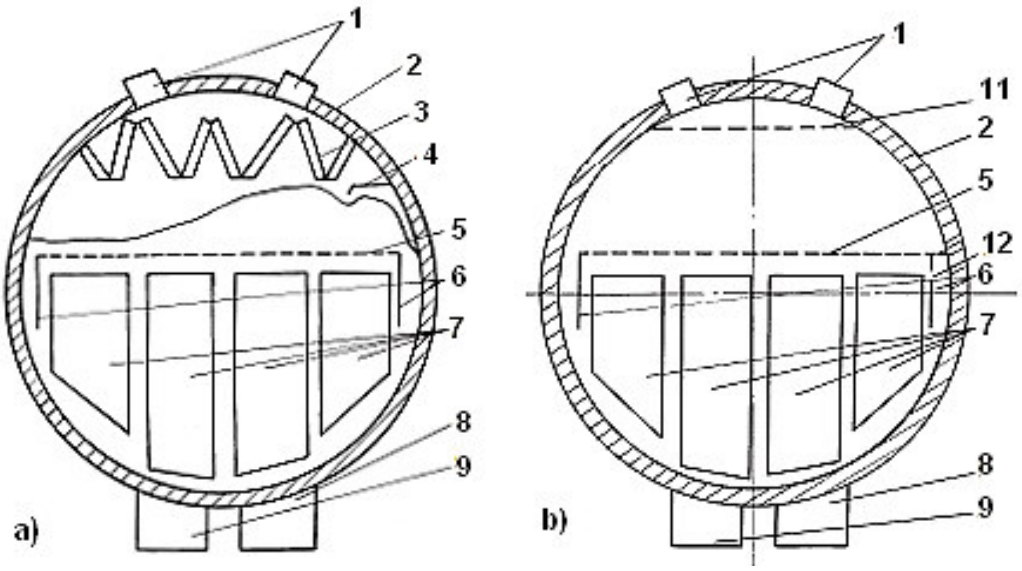

Figure 2 – Separation scheme of the horizontal steam generators: a) with louver separator; b) with shield receiving steam (1 – pipes of the steam; 2 – casing; 3 – louver separator; 4 – reflector; 5 – submerged perforated sheet (SPS); 6 – bends of SPS; 7 – packages of heat exchanging tubes; 8 – «hot» collector; 9 – «cold» collector; 11 – steam-receiving perforated sheet; 12 – overflow windows)

When replacing the louver scheme with a scheme with a ceiling shield receiving steam, the height of the steam volume increased from 750 mm to 1200...1250 mm. This led to an improvement in the separation characteristics, which has been repeatedly proven by full-scale tests [3]. Because of this, it became possible:

- to increase the coefficient reserve for steam capacity;
- to increase the safety of operation of the second circuit of NPP due to the increase in the allowable range of changes in the level of the boiler water;
- to reduce steam humidity at the output of the steam generator while increasing the steam limiting speed to 0.6...0.7 m / s at a steam humidity of 0.2%.

The conditions of control and repair of SG internals are also significantly improved.

Increasing the heating capacity of the steam generator PGV-1000MKP to 800 MW in steam capacity 1602 t/h, table 1, in the V-392M (WWER-1200) project required further improvement of the separation scheme. In the V-320 (WWER-1000) project for with a uniform perforation degree of 7.3%, the residual unevenness of the evaporation mirror load was 1.25, and the local vapor velocity on the evaporation mirror reached a value of about 0.43 m/s at maximum power [4].

The extension of the steam generator PGV-1000 MKO (WWER-TOI) by 1 meter slightly increases the hydraulic resistance of the steam generator, reduces the evaporation mirror load, but it is more difficult to equalize the evaporation mirror load and organize a uniform steam extraction [5].

In order to reduce the local speed of the output steam from the evaporation surface and reduce the moisture content of the steam leaving the steam line, a submersible perforated sheet with a variable degree of perforation has been developed and introduced into SG. This will reduce the uneven steam load on the evaporative mirror in the horizontal section SG.

For even more powerful PGV-1500 (1062.5 MW) and PGV-1600 (1087.5 MW) with economizer, together with separation schemes, other elements of the steam generating path will be improved. In particular, instead of 10 tubes of steam to PGV-1000MKP, PGV-1500 they will remain two [6], and SG 1600 – single [7].

Table 1 – Some Technical and Economic Indicators of SG

Indicators	**Models: Steam Generator / Reactor**						
	440	**1000M**	**1000MKP**	**1000MKO**	**1500**	**1650**	**SNP 140**
	WWER-440	**WWER-1000**	**WWER-1200**	**WWER-TOI**	**WWER-1500**	**WWER-TOI**	**CAP-1400**
Technical							
Number of SG per reactor	6	4	4	4	4	2	2
Thermal power, MW	229	750	800	825	1500	1650	2029
Steam production t / h	450	913	1602	1652	2150	3205	~3900
The inner body diameter / length, m	3,2 13.0	4,0 13,84	4,2 13,82	4,2 14,82	4,8 15,62	4,8 16,59	4,655 24
Mass (without supports), t	145	315	337	353	530	513	807
Number of tubes	5536	11000	10978	11000	15120	19156	12606
Heat exchange surface, m^2	2577	6115	6105	6660	9490	12343	14666
Inlet / outlet coolant temperature, ^0C	301 266	320 289	329 298	328,8 297,2	330 297,6		324 284
Coolant flow rate, m^3/h	7100	21200	21400	22000	26971	44000	21642
Hydraulic resistance in I contour, MPa	-	не более 0,13				0,61	~1,1
Economic							
Block efficiency, %	32,1	33,3	37,5	37,9	37,5	37.5	37,0
SG efficiency, %	97- 99						
Specific steam production per hour (by weight)	3,10	2.90	4.75	4.68	4.06	6.25	~ 4.83

Designing horizontal SG for new competitive Russian NPP units without the ability to increase the primary coolant flow rate can be viewed as the process of creating heat exchangers with low temperature pressure or low specific heat load of the SG heat exchange surface. Accordingly, when designing, the issues of providing heat removal with a steam generator will become more significant, and its separation characteristics will be ensured due to the low specific load of the heat exchange surface and the evaporation mirror The new steam generator PGV-1650 for the two-loop reactor WWER-TOI is a good example of increasing the thermal power of an SG due to a fundamental change in the thermal-hydraulic separation scheme [5].

For distribution of the coolant through the pipes, collectors are used, but unlike the traditional layout, they are arranged not vertically, but horizontally. From the horizontal distributing collector, the coolant is distributed to the upper half of the tube bundle, moves along pipes along the hull SG, cooling down at the same time. At the bottom of the steam generator, the pipes unfold by 180º, and the coolant moves to the collecting manifold in the lower part of the heat exchange beam. As a result, in each cross section of the steam generator, the beam is filled with upper conditionally hot and lower conditionally cold pipes. Due to this event, the vaporization along the length of the steam generator remains almost constant, that made it possible to abandon the submerged perforated sheet. The reduction of local heat loads in NG allows to increase its heat output up to 1,650 MW, which significantly increases the competitiveness of a horizontal steam generator compared to a vertical one [8, 9, 10], for example, SNP 140 Chinese project CAP-1400 [11, 12], table 1. Currently, their

specific technical and economic indicators, especially in relation to the size-weight factor, are becoming more and more important in the race of SG, table 1.

CONCLUSIONS

1. Thermal capacity of a horizontal SG of 800 MW is not limit and can be significantly increased with the elimination of the main drawback of the horizontal steam generator is significant irregularity of the heat load on the area of the evaporation mirror.

2. In the steam generator PGV-1650 for the two-loop WWER-TOI, the heat output is increased more than 2 times from existing horizontal steam generators, without significant complication of the design and the preservation of single-stage gravity-precipitation separation of steam.

3. Under the conditions of equality of thermal efficiency of modern steam generators of NPPs, their specific technical and economic indicators are crucial relative to the size-weight factor.

REFERENCES

[1] Lakhov D.A., Kharchenko S.A. About the limit power of a horizontal steam generator Materials of the conference: report, 16th International scientific and technical conference of young specialists of OKB «GIDROPRESS». 26-27 March, 2014. Podolsk: OKB «Gidropress», Russia, 2014. URL : http://www.gidropress.podolsk.ru/files/proceedings/kms2012/autorun/index-ru.htm (in Russian).

[2] Nigmatulin B.T., Ageev A.G., Blinkov V.N., Vasiliev V. R., Korol'kov B.M., Dragunov Yu.G., Trunov N.B., Nekrasov A.V., Ilyushin V.F.. Experimental study, testing and implementation of new separation scheme for steam generators of nuclear power units with WWER-1000. Nuclear power plant. 2003. № 3. P. 16-22 (in Russian).

[3] Petrov A.Yu. Modernization of separation equipment in the steam generators of NPP with WWER. PhD Thesis in Engineering 05.14.03. Moskow, 2005. 105 p. (in Russian).

[4] Trunov N.B., Lukasevich B.I., Sotskov V.V., Kharchenko S.A. The past and the future of horizontal steam generators. Materials of a seminar: report, 7-th international seminar on horizontal steam generators. 3-5 October, 2006. Podolsk: OKB «Gidropress», Russia, 2010. URL : http://www.gidropress.podolsk.ru/files/proceedings/seminar7/seminar7/section1.htm (in Russian).

[5] Lakhov D.A., Kharchenko S.A. Horizontal steam generator. Problems of increasing power and possible solutions. Materials of the conference: report, 14-th International scientific and technical conference of young specialists of OKB «GIDROPRESS». 21-22 March, 2012. Podolsk: OKB «Gidropress», Russia, 2012. URL : http://www.gidropress.podolsk.ru/files/proceedings/kms2012/autorun/index-ru.htm (in Russian).

[6] Volkov V.Y., Golibrodo L.A., Krutikov A.A., Kudryavtsev O.V., Lahov D.A., Nadinsky Y.N., Nikolaeva A.V., Skibin A.P., Sotskov V.V. Optimization of perforated distribution plate in steam generator PGV-1000MKO using CFD. Transactions of 9-th International Scientific and Technical Conference «Safety Assurance of NPP with WWER», 19-22 May, 2015. Podolsk: OKB «Gidropress», Russia, 2015 URL : http://www.gidropress.podolsk.ru/files/proceedings/mntk2015/autorun/section2-en.htm (in Russian).

[7] Emelyanov I.D. Definition of levelling ability of submerged perforated sheet variable perforation to increase the capacity of NPP with WWER PhD Thesis in Engineering: 05.14.03. Moskow, 2015. 200 p. (in Russian).

[8] Lyakishev S.L., Trunov N.B., Sotskov V.V. Analysis of steam flow in the steam collector of PGV-1000MKP SG. Materials of a seminar: report, 8-th international seminar on horizontal steam generators. 19-21 May, 2010. Podolsk: OKB «Gidropress». Russia. 2010. URL : http://www.gidropress.podolsk.ru/files/proceedings/seminar8/seminar8/section3-ru.htm (in Russian).

[9] Gritsenko A.A. New horizontal steam generator for two-loop RU high power. Materials of the conference: report, 16-th International scientific and technical conference of young specialists of OKB «GIDROPRESS», 26-27 March, 2014. Podolsk: OKB «Gidropress», Russia, 2014. URL : http://www.gidropress.podolsk.ru/files/proceedings/kms2012/autorun/index-ru.htm (in Russian).

[10] Trunov N.B., Lukasevich B.I., Veselov D.O., Dragunov Yu.G. Steam generators – horizontal or vertical (which type should be used in nuclear power plants with VVER?). Translated from Atomnaya Énergiya. Vol. 105. No. 3. P. 127-135, September, 2008. Original article submitted July 25, 2008. Springer Science+Business Media, Inc. (in Russian).

[11] In the world: Interview with the head of the development team of the technical project of the power unit with the CAP1400 reactor Fang Zhou. Atomic Expert: electron. version of the journal. 2016. № 7 (49). P. 41-43. URL : http://atomicexpert.com/atomicexpert7-2016 (in Russian).
[12] Reactor CAP1400. AtomInfo.RU: electron. period. ed. 03/05/2015. URL: http://www.atominfo.ru/newsk/r0389.htm (in Russian).

Comparative Analysis of Generating Path in Horizontal NPP Steam Generators

Michael Nii Sanka Ansah[*1] (Ghana), N.N. Podrezov[2]**

[*]National Research Tomsk Polytechnic University, Tomsk Polytechnic University, TPU, 30, Lenin Avenue, Tomsk Polytechnic University, Tomsk, Russia 634050
[**]Volgodonsk Engineering Technical Institute the branch of National Research Nuclear University «MEPhI», Lenin St., 73/94, Volgodonsk, Rostov region, Russia 347360
[1]ORCID iD: 0000-0002-0314-2413
WoS Researcher ID: G-3892-2017
e-mail: michaelansah67@gmail.com
[2]ORCID iD: 0000-0001-8957-8682
WoS Researcher ID: C-5465-2018
e-mail: VITIkafMPM@mephi.ru

Abstract – The article provides a brief overview of the effect of various separation schemes in horizontal steam generators (PGV) of nuclear power plants on the quality of steam produced in the steam path for supply to the turbine. A further increase in the thermal power of the PGV without a significant increase in the overall dimensions is determined by the «retention» of the separation characteristic of the PGV within the limits specified by the dryness of the steam taken. In this direction the key optimization of horizontal PGV should be considered the rejection of louvered separators in favor of steam-receiving perforated sheets with variable perforation and the development of a new thermal-hydraulic scheme for the two-loop WWER-TOI project.

Keywords: steam generator (SG), steam separation, WWER units, steam humidity, evaporation mirror, gravity separation, submerged perforated sheet (SPS), steam-receiving perforated sheet, technical and economic indicators.