THE PAST AND THE FUTURE OF HORIZONTAL STEAM GENERATORS

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ABSTRACT

The design concept of horizontal steam generators (SG), applied at WWER NPPs, differs from the design concept of vertical SGs applied at NPPs of the most western countries. Nowadays all over the world there are 270 SGs in operation at Units with WWER-400 and WWER-1000, and some Units are under construction. Operation experience showed that the horizontal SGs have a number of advantages from the viewpoint of both reliability, and safety. The report deals with consideration of the design concept of SGs applied at WWER NPPs as compared to vertical SGs.

The effect of SG design on thermal efficiency and engineering and economic indices is analysed. The ways of improving the efficiency of horizontal SGs are described. The selection of tubing material and a possibility of assuring the tubing reliable operation throughout the design service life are considered. The operation experience is analyzed and the ways of solution of the occurred problems are shown.

In the future, the operational performance of SGs for WWER NPP will be improved as a result of theoretical and experimental studies. A description is given for the ways of design development on the basis of operation experience. It is shown that the basic design solutions for the horizontal SGs can be used for new Units of power to 1600 MW.

INTRODUCTION

The important components of NPP with the pressurized water reactors (WWER and PWR) are the SGs generating steam to the turbine generator for producing the electric power. In the USA and USSR (countries that laid down the foundation of nuclear power engineering) the principally different layout and design approaches to creation of steam generators are established historically. If we degress from the first test and searching solutions, the situation is the following – vertical steam generators are installed at NPPs with PWR, and horizontal steam generators are installed at NPPs with WWER. Both types of steam generators fulfil their functions rather satisfactory and provide for NPP operation.

At present the SGs of PGV-440 and PGV-1000 types are used at NPPs with WWER. Figures 1 and 2 demonstrate the general views of these steam generators. Their design, as compared to the original design, was subject to changes and modifications in the course of operation. The process of improving the operating SGs is under way, ref. [1].

At a number of NPPs the steam generators of PGV-440 type are operated at present beyond the design service life of 30 years. Maximum operating life of PGV-1000 has reached more than 150 thousand hours. Totally, 162 steam generators of PGV-440 type and 108 steam generators of PGV-1000 type are in operation.

Nowadays, alongside with PGV-440 and PGV-1000, there are other designs of horizontal SGs under different stages of development, for instance, steam generator PGV-640 designed for the reactor plant of medium power. The steam generator PGV-1000У is manufactured and ready for application, the perforated part of the collector in this steam generator is made of stainless 08Х18Н10Т-ВД. For the plants of increased power the designs of PGV-1500 and PGV-1600 are developed. Design features of these SGs are considered in ref. [2]. Table 1 gives the main technical data on SGs starting from the first standard SG of Unit 3, NV NPP.

Table 1

Main technical data on SGs

Name	PGV-440	PGV-640	PGV-1000М	PGV-1000У	PGV-1000МК	PGV-1000МКП	PGV-1500	PGV-1600
Thermal power, MW	229	450	750	750	750	800	1062,5	1087,5
Steam capacity, kg/s (t/h)	125 (450)	254 (913)	408 (1470)	408 (1470)	408 (1470)	445 (1600)	598 (2150)	613,8 (2210)
Pressure of steam generated, MPa	4,61	7,06	6,27	6,27	6,27	7,0	7,34	7,80
Steam temperature, °C	258,9	286,5	278,5	278,5	278,5	287	289,0	293
Coolant temperature at the inlet/outlet, °C	297/270	322/295	320/289	322/292	321/291	329/298	330/297,6	330,2/298,6
Coolant temperature, MPa	12,26	15,7	15,7	15,7	15,7	16,14	15,7	16,2
Coolant flow rate, m^3/h	7100	14000	21200	21500	21500	21400	26971	28440
Feed water temperature, °C	164 - 223	164 - 230	164 -220	164 -220	164 -220	225	187-230	164-230
Average reduced steam rate on evaporation surface, m/s	0,21 [1)]	0,24	0,31 [2)]	0,31 [2)]	0,30 [2)]	0,33 [2)]	0,29 [2)]	0,27 [2)]
Unit heat load of the heat transfer surface, kW/m^2 [3)]	90	106	123	146	123	131	112	118
Vessel diameter (inside), m	3,2	3,8	4,0	4,0	4,2	4,2	4,8	4,8
Vessel material	22К	10ГН2МФА	10ГН2МФА	10ГН2МФА	10ГН2МФА	10ГН2МФА	10ГН2МФА	10ГН2МФА
Material of the collector perforated part	08Х18Н10Т	08Х18Н10Т-ВД	10ГН2МФА-Ш	08Х18Н10Т-ВД	10ГН2МФА-Ш	10ГН2МФА-Ш	10ГН2МФА-Ш	10ГН2МФА-Ш
Economizer available	no	no	no	no	no	no	no	yes
Diameter of heat exchanging tubes, mm	16	16	16	16	16	16	16	16
Thickness of heat exchanging tubes, mm	1,4	1,5	1,5	1,5	1,5	1,5 1,4 [7)]	1,5	1,3/1,2 [5)]

Table 1 continued

Spacing (vertical/horizontal) in evaporator, mm	24/29,5	25/23	19/23	22,1/25	22/24	22/24	22/24	22/24
Spacing (vertical/horizontal) in economizer, mm	-	-	-	-	-	-	-	20/19
Arranging of tubes in evaporator in economizer[4]	corridor	corridor	staggered	staggered	corridor	corridor	corridor	corridor staggered
Heat exchange surface, m^2	2577	4223	6115	5127	6105	6105	9490	9212
Number of tubes	5536	8320	11000	9157	10978	10978	15120	14750
Average length of tubes, m	9,26	10,10	11,10	11,14	11,10	11,1	12,50	12,43
Submerged perforated plate available	no [6]	local	yes	yes	yes	yes	yes	yes
Blinds separator available	yes	no	no [7]	no	no	no	no	no

[1] reduced to the area limited by the outer rows of tubes from the vessel side
[2] reduced to the area of submerged perforated plate (SPP)
[3] over outer surface of tubes
[4] arranging of tubes in the bundle is determined relative to vertical direction
[5] for the version with alloy 03Х21Н32М3Бу-ВИ (ЧС-33)
[6] at some Units the local SPP is placed
[7] available in SGs manufactured before 1990

COMPARISON OF SGs AT WWER AND PWR NPPs

From the moment of appearance of the pressurized water reactors in the USA and USSR the two different design concepts of SG were outlined – vertical and horizontal. In the first case - the vertical vessel and U-shaped heat exchanging tubes embedded into the horizontal tube sheet, in the second – the horizontal vessel and horizontal coils of heat exchange surface embedded into the vertical primary side coolant collectors. Selection of the tubing material was also principally different – high-nickel alloys or stainless steel. At present we can only conjecture the considerations followed by the designers in 50-60-ties when selecting one or another structure. Probably they considered the problems of arranging the equipment, thermal-hydraulics and layout, a possibility of using the available and approved process of manufacturing. Evidently, at that time the economic considerations were taken into account also, and the experience in manufacture and operation of heat exchanging devices of traditional power engineering played an important role.

- Nowadays we can ascertain the fact that both design concepts are finally the stable trends with a rich history including successes and errors. Operation experience showed the weak points of structures that were eliminated with accumulation of this experience. Unfortunately this experience resulted sometimes in replacements of SGs. Some problems arisen in SG operation will be considered below, and, at the beginning, we'd like to remind of the main advantages of the horizontal steam generators as compared to the vertical steam generators:
- moderate steam load (reduced velocities of evaporation surface is 0,2-0,3 m/s) makes it possible to use a simple separation scheme with the reliable steam moisture required;
- moderate velocities of the secondary side medium (up to 0,5 m/s) exclude a hazard of vibration of SG heat exchanging tubes and other components and remove a problem of damage caused by foreign objects;
- with the accepted water chemistry the application of rather cheap stainless austenitic steel 08X18H10T with low nickel content is justified for heat exchanging tubes. The steel serviceability is confirmed by operation experience of steam generators PGV-440 and PGV-1000 at WWER (operating life is more than 30 years);
- vertical cylindrical primary side collectors make it possible to avoid accumulation of sludge deposits on collector surfaces and, hence, to reduce a hazard of corrosion damage of coils in the region of embedment into the primary side collectors;
- there is an increased water inventory in the secondary side facilitating the reliable reactor cooling down through SG in case of loss of normal and emergency feedwater supply; high accumulating capacity of SG makes the RP transients moderate;
- application of the stepwise evaporation principle allows to maintain the concentration of dissolved impurities in SG critical areas several times less than the balanced concentration in the blowdown water that improves considerably the SG operation reliability from the viewpoint of corrosion;
- horizontal arrangement of heat exchange surface provides for reliable natural circulation of medium on the primary side, even with decrease in water collapsed level below the upper rows of heat exchanging tubes;
- there are favourable conditions to assure the natural circulation of the primary coolant under accidents. Accumulation of noncondensible gases, impeding coolant circulation, is prevented. Presence of large gas receivers (up to 0,5 m^3) in the upper parts of vertically installed coolant collectors provides for easy gas disposal from the tube bundle into the gas removal system;

- a convenient access is provided to the tubing for maintenance and inspection both on the primary, and secondary side. There are no heat exchanging tubes in the lower points of SG vessel, wherein sludge deposition and accumulation is possible. In case of accumulation of corrosive impurities in the vessel lower part, their washing off is possible through the system of SG blowdown and pipe sleeves specially provided;
- for vertical coolant collectors the equipment for SG isolation from the main coolant piping is mastered, that allows to reduce considerably the duration of preventive maintenance and to increase the load factor.

Specific feature of the vertical SG is application of relatively long heat exchanging tubes (about 20 meters), as compared to the horizontal steam generator (for PGV-1000 the average length is about 11 meters, for PGV-1500—12,5 meters), that makes possible to reduce their number in the bundle and to get the higher coolant velocities over the primary side (approximately 1,5 times), as well as to increase the thermal efficiency (reduction of heat exchange surface) approximately by 7 %. On the other hand, application of long tubes reduces the SG “survivability” because a high structural margin of the surface is required for plugging of failed heat exchanging tubes.

Saving of metal and reduction of construction scope are often related to the advantages of the vertical SGs, as compared to the horizontal SGs. These statements are to be analyzed in detail. As noted by the authors of ref. [3], in spite of the known deficiencies, for instance, sludge accumulation, the vertical steam generators are applied at PWR NPPs because the areas are saved and the construction work is reduced. This widespread thesis is not quite true. In the course of designing the RP for WWER-1500 it was found that determination of the containment overall dimensions was not connected with the layout of steam generators. Investigations and design studies performed in the USA, ref. [4], showed that application of horizontal instead of vertical steam generators makes an insignificant effect on the volume and cost of the containment.

To compare the specific amount of metal for structures of vertical and horizontal SGs the thermal efficiency of one or another structure shall be considered. In other words, we shall understand which structure allows to achieve the higher steam parameters with the similar weight and overall dimensions, or which one has the less weight and overall dimensions with similar parameters. This question can not be answered simply because in comparison of the finished structures the difference in parameters, design standards, materials, etc. shall be taken into account.

First of all, it should be noted that the heat transfer modes in SG evaporating part do not depend on arrangement of heat exchange surface because inside the tubes there is a convective heat transfer, and outside the tubes – the developed boiling.

As to the economizer section, it can be implemented differently. In the known vertical SGs it is made by cross flowing over the tubing with inclusion sequentially over the primary coolant path. In the horizontal SG the scheme of parallel-mixed flow is more convenient (see, for instance, ref. [5]). The solution with application of the economizer entails a number of problems for both SG concepts, but, finally, allows to increase the generated steam pressure by 0,3 MPa, approximately.

In comparing the SG versions the increase in thermal efficiency due to decrease in the heat exchanging tube wall thickness shall be also considered. At PWR NPPs the considerably less safety factors and margins are taken that makes possible to obtain the relative wall thickness about 1,7 times less than at WWER NPPs, and, accordingly, higher steam pressure[1]. For PGV-1600 design a possibility of decrease in the wall

[1] *Tube size in PGV-1000 is 16,0x1,50 mm, Model F Westinghouse – 17,47 x1,02 mm with close mechanical properties of materials..*

thickness was studied considering strength standards and specifying the process and corrosion margins. It is shown that with decrease in tube thickness by 0,2-0,3 mm the increase in steam pressure is possible by 0,1-0,15 MPa.

It should be kept in mind that decrease in the heat exchanging tube wall thickness leads, on the one hand, to increase in thermal efficiency, and, on the other hand, to decrease in reliability and safety due to increase in rupture probability that took place repeatedly at PWR NPPs. For SG heat exchanging tubes at WWER NPPs the critical size of longitudinal defect is considerably greater and easier to be detected in due time by the sign of a leak, or using the non-destructive methods, that makes possible to plug the failed tube for preventing a large rupture and possible release of radionuclides into the environment.

So, considering introduction of the economizer and application of heat exchanging tubes of decreased thickness, we obtain the characteristics of the horizontal steam generator PGV-1500 (PGV-1600) at the level of those at EPR plant, including the specific amount of metal (see Tables 1 and 2).

Table 2

Comparison of technical data between steam generators PGV-1600 with economizer and EPR

Parameter	PGV-1600	EPR
Nominal thermal power, MW	1087,5	1125
Steam capacity, t/h	2210	2554
Steam pressure at the SG outlet, MPa	7,80	7,80
Steam temperature, ^{o}C	293,2	293,2
Coolant temperature at the SG inlet, ^{o}C	330,2	327,2
Feedwater temperature, ^{o}C	230	230
Moisture of generated steam at the SG outlet, % of masses, not over	0,2	0,1
SG water inventory, t	96	89
Vessel outside diameter, m	5,21	5,04
Vessel length, m	15,62	23,00
Heat exchanging tube material	08Х18Н10Т/ 03Х21Н32М3Бу-ВИ (ЧС-33)	Inconel 690
Number of heat exchanging tubes, pcs.	14750	5980
Outside diameter of heat exchanging tubes, mm	16	19,05
Wall thickness of heat exchanging tubes, mm	1,3/1,2	1,09
Heat exchange surface, m^2	9212	7960
Mass of steam generator (without supports), t	540	551

Finally, it can be stated that heat transfer efficiency in the process of boiling with the available parameters of the primary side medium does not depend strongly on SG design solutions, that is, no one of design concepts has advantages in terms of specific amount of metal.

According to the information available, foreign designers are involved in development of application of horizontal steam generators for new NPP projects, ref. [6]. Nevertheless, despite separate shortcomings, the basic design lay-out and the type of vertical steam generator at PWR NPP remains the principal direction in steam generator industry stipulated by operational feedback from NPPs and a reliable operation at a lot of Units observing the design conditions. Russian designers hold conceptually the same ground with regard for evolutionary perfection and development of steam generators.

CORROSION AND SELECTION OF MATERIALS

Problems of vertical SGs are caused, to a considerable extent, by corrosion. The only exceptions are the problems of tube vibration wear either in U-section, or in the economizer, and also the tubing damage because of impacts of foreign objects. Horizontal SGs did not suffer mechanical damages owing to moderate velocities of the secondary side medium. Thus, the horizontal SGs were also faced basically with corrosion, ref. [7].

To date, a great scope of investigations of the vertical SG corrosion mechanisms makes possible to study the main modes and conditions of corrosion mechanisms, ref. [3]. There is a conceptual unremovable shortcoming in the vertical SGs - a horizontal tube sheet wherein a sludge is accumulated. As noted by the authors of ref. [8], the heat exchanging tube corrosion in the area of tube sheet can be prevented only by absence of sludge. But it is a very hard problem to achieve this. In any case, routine and thorough mechanical or chemical cleaning is required. In the horizontal steam generators the sludge depositions are on the vessel lower part that facilitates their removal. Nevertheless, washing of the tube bundle is still necessary. In case of application of sparse corridor arrangement of tubes in the bundle, the problem of accumulation and removal of sludge becomes of less concern.

In comparing the operational feedback of the vertical and horizontal SG tubing in terms of corrosion it shall be taken into account that the horizontal SGs are mainly operated under drastically worse water chemistry, ref. [9].

As to the level of maintaining water chemistry, a majority of WWER NPPs happens to be well behind the leading nuclear countries (the USA, France, Germany). As operational feedback at WWER-1000 NPPs accumulated, taking into account water chemistry maintenance at foreign PWR NPPs, the home water chemistry standards were revised both to the side of decreasing the content of corrosive impurities in feed and blowdown water, and of imposing limitations on additional parameters (e.g. sulphate-ions). For more than 20-year operation period, the normal content of chlorides in steam generator blowdown water was decreased from 500 to 100 μg/kg, of sodium - from 1000 to 300 μg/kg, and pH parameter was increased from 7,8-8,8 to 8,5-9,2. Content of sulphates in blowdown water has been standardized only since 1997. Nevertheless, the water chemistry parameters achieved are still below the world level, as, for example, content of chlorides, sodium and sulphates in blowdown water at the operating NPPs is 5-15 times higher than at NPPs abroad. Actual content of ferrum in feedwater is remarkably higher than that at foreign Units where morpholine and ethanolamine modes are used. At NPPs being built anew this difference will be considerably less.

Further making the standards more stringent – decrease in content of corrosive impurities in feed and blowdown water is kept back, in the first place, by the necessity of replacing the main condensate system basic equipment – condensers and heaters. Selection of equipment for the majority of currently operating WWER-1000 Units was based on the experience of thermal power and operational feedback of WWER-440 tubing - positive at that period of time. Equipment made of copper-bearing alloys, condenser leakiness and the heaters with insufficient corrosion resistance do not make it possible to maintain the water chemistry at the up-to-date level. Considering the necessity to extend the SG service life it can be stated that the main condensate system basic equipment should be replaced. NPP "Kozloduy" and NPP "Paks" followed this way, whereas at NPP "Temelin" and NPP "Loviisa" the replacement was done from the very beginning of operation. No doubt, this problem shall be solved positively during construction of new Units.

Results of studies and operational feedback are indicative of the fact that the tubing made of austenitic steel is highly resistant to corrosion with no surface fouling and conditions for local evaporation. At the same time, mass tubing damages took place at a number of Units. All of damages are referred to SGs operated for a long time without chemical washing under the conditions with violation of water chemistry requirements and with leaks of condensers. The main cause of damages is inadmissible surface fouling of heat exchanging tubes, as well as sludge deposition, leading in some cases to complete blocking of the shell side. It is possible to prevent the increased fouling of heat exchanging tube surface with the help of chemical washings to be performed in due time. It should be noted that prior to implementation of eddy-current test at WWER NPPs, enabling to assess the heat exchanging tube state and time history of corrosion process, the problems of tubing corrosion were underestimated. The state was to be judged by occurrence of inter-circuit leak, that is, the cases of a through-wall damage of heat exchanging tube. At the initial period of operation there were few cases like that and the problem was solved by plugging the failed tubes. Deposits and their amount were not inspected by the same cause and, in addition, there were no washing procedures mastered actually.

Analysis of SG state at NPPs in Russia, ref. [10], showed a difference between SGs in terms of tubing state even within one Unit, that testifies to different operation conditions of these SGs. A number of SGs is still subject to a process of intensive degradation and a residual service life of heat exchanging tubes is to be confirmed, for example, SG No.4 of Balakovo NPP, Unit 3, and SG No.4 of Novovoronezh NPP, Unit 3. At the same time, there are steam generators exhibiting good state after operating life of about 150 000 hours, for example, steam generators of Kalinin NPP, Unit 2. At a number of SGs a stability, and even improvement, of corrosion state time history is observed. As a rule, it is related to quality of water chemistry maintenance and performing the chemical washing in due time. Having a significant operating period, the SG tubing is in perfect state at "Loviisa" NPP, "Kozloduy" NPP, Unit 6, Khmelniski NPP, Unit 1, and at a number of other NPPs.

As to the vertical SGs, there are also positive examples of a long-term defect-free tubing operation. It is not referred to the first generation of SGs with the tubing of Inconel-600 and unsuccessful design of spacing grids when practically all SGs were replaced. Alongside with this, despite a great success in water chemistry maintenance, duration of operation of new SGs with the tubing of alloy 690 still does not make possible to state that corrosion is prevented completely.

The problem concerning possible prevention of SG tubing corrosion is the most important for selection of SG design for the future prospect. As seen, there are positive examples indicative of a possibility to solve the corrosion problems within the framework of both design concepts considered. The assessments of the possibility to operate the stainless steel tubing up to 40-60 years are available both in western countries and in Russia, ref. [11]. For the proper confirming and justifying this possibility and determining the required conditions the R&D program is planned, ref. [7].

It is seen from the above mentioned that application of stainless steel has prospects as a material for the tubing in new SG designs. The steel advantages: rather low cost, optimized technology. The low content of nickel in comparison with high-nickel alloys makes possible the solution of the problems of the primary circuit equipment activation owing to cobalt. Should the stainless steel be considered as a single version? The world experience shows that in spite of application of rather corrosion-resistant high-nickel alloys, the serious corrosion problems still took place in SGs at PWR NPPs. Thus, the most important factors are the operation conditions that provide for suppression of corrosion processes under all operation modes. This can be achieved both for stainless steel, and for alloys of types 690 and 800. Another thing is the cost of this under actual operation conditions. The stainless steel, unlike the high-nickel alloys, is susceptible to chloride stress corrosion, and this is its main disadvantage. Water chemistry in the course of SG operation should exclude the conditions for initiation of the given kind of corrosion, because there is no oxygen in water, and the content of chlorides, sulphates and other impurities is stringently standardized. At the same time, the local points of accumulation of corrosion product deposits on the tubing can lead to accumulation of chlorides up to the values being some orders higher than the normal values. The effect of other oxidizers is possible instead of oxygen, for example, copper. Thus, either violation of water chemistry, or the uncontrolled processes during local evaporation of medium under deposits, lead to corrosion cracking of stainless steel. The special measures should be taken to ensure suppression of corrosion under shutdown or startup conditions, when air oxygen gets into SG.

All these circumstances induce us to search for additional measures to enhance the tubing corrosion resistance, alongside with improving the water chemistry. The alternative to stainless steel can be, for instance, the high-nickel alloy of grade 08Х20Н32М3Б (ЧС-33), that is a close analog of alloy 800 with a positive operation experience. The alloy ЧС-33 allows to achieve the higher corrosion resistance of SG tubing to pitting and corrosion cracking. This makes steam generator more resistant to possible violations of design conditions for storage and operation. At the same time, the given alloy is noticeably more expensive than the stainless steel, and higher concentration of nickel could make the radiation situation during RP operation more severe. The alloy has the lower heat conduction in comparison with the stainless steel, that is compensated by higher mechanical properties for decrease in wall thickness. So, there may be two SG design versions with similar (slightly different) values of weight and overall dimensions and thermal-hydraulic characteristics. The design version should be chosen by a consumer with regard for economic considerations, operation conditions (cooling water of the condenser and its tightness, climate), and also capabilities for provision of high standard of operation culture.

A conclusion can be drawn that considering a possibility of material replacement and other design features of the horizontal SGs, they have the greater capabilities for ensuring defect-free operation of the tubing in comparison with the vertical SGs.

OPERATION EXPERIENCE

Serviceability of PGV-1000 collectors

At the end of 1986 the cracks were revealed for the first time on the "cold" outlet coolant collectors of PGV-1000 steam generators. The cracks occurred in the ligaments between tube holes in the region of the so-called “wedge” of the collector perforated part, wherein the area of concentration of residual and operational stresses was located. In the period till 1991 the similar defects were detected in 24 SGs more. In most cases the affected SGs were replaced, and in two cases they were repaired using the specially developed process. The studies have shown that the cracks extended from the crevice area between a tube and a collector, on the secondary side, up to through-wall cracks, with the damage to welds of heat exchanging tubes. As a result of studying the causes and mechanism of damage to collectors it was found out that the given phenomenon is a new one in the practice of steam generator building.

The damages in the form of cracks were detected only on the "cold" collectors, that gave the ground to consider the operating temperature of the "cold" collector metal an important factor, at which a sudden decrease (by a factor of 8-10) in metal plastic properties was observed under the effect of corrosion medium.

The high level of engineering elastic residual stresses up to 855 MPa was revealed in collectors after the process of explosion expansion of heat exchanging tubes. It was found out that at the operating temperature of the "cold" collector and with the total stresses close to yield strength, the steel 10ГН2МФА has a low-temperature creep. As a result of the complex of studies, the initial stage of damage was qualified as a corrosion cracking at slow strain rate, ref. [12].

To solve the problem of collector cracking the complex of measures was implemented aimed at changing the manufacturing process, modifying the design, making the water chemistry requirements more stringent, improving the testing methods.

The implemented measures made possible to solve the problem of damage to SG collectors at WWER-1000 NPP Units. Since 1991 no SGs have been replaced due to cracking of collectors. For newly manufactured steam generators the design service life of up to 60 years is provided.

Solution of the cracking problem in PGV-440 collectors

Since 1975 the problems of metal cracking have occurred in the collector weld area located under the protective housing made of steel 08X18H10T (see Fig. 3), similar to the collector. Almost at all WWER-440 Units, that had been operating by that time (NV NPP, Kola NPP, Armenian NPP, NPP “Nord” and NPP “Kozloduy”) the cracks of different depth, up to the through-wall cracks and initiated on the secondary side, were revealed in collector metal. The studies of this phenomenon were carried out including studies on the model constructed specially. It was found out that failure of collectors has occurred as a result of chloride corrosion cracking on the secondary side. The cracking was caused by getting of the secondary side water into the cavity under the protective housing; the repeated evaporation of this water has resulted in stress cracking of the collector metal. The causes of this phenomenon were the poor welded joints of the housing, the lack of its tightness check during SG operation.

The repair of collectors was carried out by eliminating (grinding out) the cracks and closing these places by melting the stainless metal with the appropriate inspection. In some cases the upper flange part of collectors was replaced.

The problem of reliable operation was solved by filling the sealed cavity of housings with nitrogen and continuous pressure monitoring system. For newly manufactured SGs the structure of the housing and its welded joints was improved.

At some SGs the solution with the unsealed housing relieved from pressure and its periodic washing, and also with the corrosion-resistant cladding of the collector surface without the housing, has been successfully applied.

Corrosion cracking of studs and their seats in PGV-440 collectors

One of the problems we have faced with during operation of PGV-440 was corrosion cracking of studs and their seats in the upper part of the primary side collectors. The collector is made of austenitic steel 08X18H10T, and the studs are made of steel XH35BT-ВД that exhibits high resistance to chloride corrosion cracking. For the various Units the character and places of cracking were somewhat different. The cracking character on the studs was intercrystalline and mixed, on the flanges - transcrystalline, in the main.

The cracks in the seats were removed by repair. In this case at a number of Units the upper flange part of the collectors was completely replaced.

The numerous studies of this phenomenon did not reveal the unambiguous cause of the cracking.

All the researchers finally point out the influence of four phenomena:

- corrosion effect of the stud lubricant based on molybdenum disulfide;
- effect of secondary side water under off-design conditions (water ingress on the flange joint from the SG water volume);
- effect of alkaline medium formed in case of malfunction with the primary side leak through both gaskets of the flange joint;
- high operational stresses.

For reliable operation of the flange joint the following measures have been implemented:

- replacement of the stud lubricant with the graphite or copper-graphite lubricant;
- maintenance of such water level in the SG that excludes operation with deviation from the design value;
- improvement of the design of the stud and flange joint components to prevent the primary side leakage;
- improvement of the studs tightening process that excludes exceed of design stresses;
- use of the expanded graphite gaskets instead of the nickel gaskets to reduce the stud tightening force.

The expanded graphite gaskets have been used since 1999 at a number of NPPs in Russia and abroad.

Application of such gaskets allows for the stud tightening force to be decreased 1,5 times. Together with the rest of the measures listed and recommended for implementation it gives the grounds to consider that the problem of excluding damage of studs and flange joints has been solved.

Problem of erosion - corrosion of feedwater collectors

During operation of a number of WWER-440 and WWER-1000 Units the corrosion-erosion wear was observed on the feedwater collectors made of carbon steel. At a number of Units the through-wall defects were revealed on the collectors.

The studies, ref. [13], were performed aimed at investigation of this phenomenon and its possible consequences. The studies showed that damages of the distributing nozzles have an insignificant effect on the SG hydrodynamics, on the whole, and its separation characteristics. The same is referred also to the temperature operating conditions of heat-exchanging tubes in case of damage of the distributing nozzles. However, it should be noted that damage of the piping in the T-piece area can cause getting of subcooled water on the coolant collector thereby leading to inadmissible thermal cycling.

The drastic solution of the feedwater collectors problem is their replacement with the new stainless steel collectors, that has been realized at the majority of WWER-1000 Units and at a number of WWER-440 Units.

Studies of welded joint No 111 cracking causes

The first case and the problem of metal cracking in the area of collector-to-SG vessel welded joint (see Fig. 4) occurred for the first time in 1998 at NV NPP, Unit 5. Then the similar damages were revealed at some more SGs; owing to this fact we had to consider this problem as a system problem of common causes. To reveal the factors resulting in cracking the considerable scope of R&D was carried out:

- detailed calculational studies of the stressed state due to operational factors;
- analysis of manufacturing process and metal properties;
- evaluation of residual stresses due to manufacturing process;
- experimental studies of the stressed state of the joint on models and at NPP;
- measurements and analysis of the RP equipment displacements during thermal expansion;
- determination of critical crack sizes.

Despite the fact that the stresses in the given joint fall within the standardized values, in combination with the stresses from off-design loadings and residual stresses, the former make a considerable contribution to damageability of the given joint. The studies showed that the damages occur due to combination of the damaging factors including a high level of stresses, temperature and corrosive environment.

The results of studies make possible to single out the major factors governing the damage process:

- off-design stressed state in case of obstacles to free SG displacement;
- clogging of blowdown lines from SG collectors and accumulation of corrosion deposits in the collector "pockets", including copper compounds causing large pits and cavities with crack nucleus in the damage area;
- technological heredity caused by procedures of machining, explosive expansion of tubes, welding and heat treatment;

Basic trends in the work on compensation of damaging factors:

- monitoring the thermo-mechanical loading of the joint during operation and analysis of actual state;
- check of value and character of equipment displacements, comparison with the design values;
- check and maintenance of cleanness of the collector "pockets" due to efficient blowdown and washing, if required;
- prevention of deviations from the prescribed SG water chemistry.

Regarding the last factor a basic solution is exclusion of the equipment made of corrosion-susceptible materials and copper-bearing alloys from the secondary side of WWER NPP.

The SG safe operation is assured by regular ultrasonic test that makes possible to reveal defects at the early stages of their development.

The solutions for new SG designs are developed that provide for decrease in stress level in the given area and removal of deposits in "pockets", aimed at excluding of such phenomena.

Level measurement

Level measurement systems in steam generators have been refined sufficiently to provide reliable level monitoring and control. In the course of gaining the SG operational experience these systems have undergone long-term evolution through improvements. Nowadays the systems with various types of levelling tanks with the base of 630 mm, 1000 mm and 4000 mm are used to measure level and to generate the protection and interlocking signals. These systems give objectively the different indications when measuring the two-phase mixture level that somewhat complicates formation of algorithms for operation of process protections and interlockings. Requirements for independence of measuring channels result in the necessity of increasing the number of levelling tanks that complicates the SG design. So, the question is ripe on unification of the applied measuring tanks that is planned to be done when developing the new SG designs.

In particular, PGV-1500 design makes use of the unified one-chamber levelling tanks with the base of 1600 mm to control level and to implement the whole range of protections and interlockings. Besides, there is the one-chamber tank with the base of 6300 mm to control level at filling, and the two-chamber tank with the base of 1000 mm to control level above the SPP.

As seen, all the essential problems occurred during SG operation have been solved within a framework of this design concept that testifies to a possibility of its further evolutionary development and perfection.

Requirements for new designs and development of the structure

Main requirements for new SG designs:

- evolutionary principle of development with maximum use of the positive experience gained;
- SG layout and design of its components shall provide the required steam capacity and parameters under all NPP operating conditions;
- all the SG components shall be reliable and safe in operation;
- possibility of corrosion processes shall be excluded or reduced essentially;
- SG design shall be simple, easy in mounting and operation, the time and dose commitments during maintenance and repair shall be minimized;
- SG overall dimensions shall provide a possibility of its arranging within the containment of assigned sizes;
- transportation problems shall be solved when manufacturing and delivering to the NPP site;
- disadvantages available in the steam generators of WWER-440 and WWER-1000 plants shall be eliminated or compensated.

Let's consider the main solutions using the steam generator PGV-1000MK as an example.

The steam generator PGV-1000MK (Figure 2) is a modification of the standard PGV-1000M made to reach the higher reliability and safety characteristics, to improve the operating conditions and maintenance. The SG vessel diameter has been increased by 200 mm that allowed to implement a number of new engineering solutions.

The main design feature of this SG is application of sparse corridor arrangement of tubes in the heat exchanging tube bundle, that allows:

- to increase circulation rate in the tube bundle thereby reducing a probability of damage to heat exchanging tubes owing to decrease in the rate of deposits growth on heat exchanging tubes and decrease in concentration of corrosive impurities under them;
- to decrease a possibility of clogging the shell-side with the loosened sludge;

- to facilitate access to the shell-side for inspection of heat exchanging tubes and their cleaning, if required;
- to increase water inventory in the steam generator;
- to enlarge the space under the tube bundle for easy sludge removal;
- to improve stressed state of the coolant collector.

With the use of the tube bundle corridor arrangement its pressure loss over the secondary side is less as compared to the staggered arrangement. The corridor arrangement is more vacant almost by 15 % (on the shell side) than in PGV-1000M with the staggered arrangement. Figure 5 shows the tube bundle arrangements in PGV-440, PGV-1000, and a new optimized version of arrangement.

To make circulation more intensive and to increase reliable operation of the SG tubing the provision is made for distribution of a portion of feedwater flow into the downcomer.

In the corridor bundle the rate of deposits accumulation on the heat exchanging tubes will decrease significantly. The formed and loosened sludge will be free to fall down between the rows of tubes and the enlarged space under the tube bundle will make it possible to remove the sludge effectively from the vessel lower generatrix.

In this particular SG, with increase in the height of heat exchanging tube bundle because of the corridor arrangement of heat exchanging tubes, the height of separation space remains unchanged practically that permits to assure the design steam moisture.

It should be noted that further power increase in PGV-1000MK, to be used in RP design for AES-2006, requires improving the separation scheme and, in particular, the submerged perforated plate (SPP). For the SPP, applied presently with the uniform perforation 7,3 %, the residual non-uniformity of loading the evaporation surface is 1,25, and the local steam rate on the evaporation surface reaches approximately 0,43 m/s at maximum power.

Steam moisture for such rates at maximum water level above SPP of 250 mm approaches the permissible value.

To reduce the local steam rate from the evaporation surface and to decrease the steam moisture at the outlet of SG steamline the application of the SPP variable perforation was studied that will allow to decrease the non-uniformity of loading the evaporation surface over the SG cross-section. The respective R&D activities are planned to verify this solution.

The steam generator PGV-1000MKП of increased power under development is a modification of PGV-1000MK that will allow to provide the higher steam capacity and higher pressure of steam generated.

Advantages of PGV-1000MK and PGV-1000MKП:

- intensity and flow rate of continuous and periodic blowdown have been increased;
- expanded graphite gaskets have been applied to seal the SG flange joints, their advantage is described above;
- wash-off devices have been implemented (detachable pipe sleeve on the vessel lower generatrix and on the reducing rings of coolant collectors) to remove sludge from the lower rows of heat exchanging tubes and SG vessel during preventive maintenance.

The collector-to-SG vessel welded joint design has been optimized that allows to decrease significantly a level of operational stresses and to exclude the conditions for corrosion cracking in the area of welded joint No. 111.

Design of SG nozzles allows to make the dissimilar welded joints under shop conditions that improves operational reliability of the given joint.

Positive features of such SG design, with account for up-to-date requirements for water chemistry, enable to consider justification of extending the service life up to 50 and more years, that makes this SG design perspective for application in new WWER-1000 RP with extended service life.

It should be noted that in spite of increase in the vessel diameter the steam generator falls within the existing layout of WWER-1000 NPP Unit.

The PGV-1500 steam generator design, mentioned at the beginning of this paper, is an evolutionary continuation and development of experience and achievements in designing the steam generators for WWER NPP.

The design inherited all the basic positive properties of the horizontal SG, and its function is to reach the up-to-date characteristics and parameters of large-power NPPs including their competitiveness in the world market of power production. The sparse horizontal arrangement of tube bundle is used with all advantages of this solution, mentioned above. A provision is made for a possibility of delivering the SG with the tubing of ЧС-33 alloy as in PGV-1000МКП.

The specific features of this structure (except those specified for PGV-1000MK) are a compactness of the layout in a set of RP owing to absence of steam header, the increased radii of tube bends to improve the testability for inspection by ECT method, an access to tubing from the bottom is made easier due to nozzles provided specially.

Application of level gauges with the extended range of measurement allows to unify surge tanks and to simplify significantly the arrangement of protections and interlockings. By present, such level gauges have been tested successfully at Volgodonsk NPP.

During SG maintenance the remote devices for control and repair are provided, their application makes possible to reduce the time period and dose commitments when servicing.

The main result of the design development is reaching the parameters and characteristics corresponding to the level of new designs of western NPPs, in particular, the EPR.

Owing to optimization of parameters the steam pressure can be increased up to 7,34 MPa, and with presence of the economizer - up to 7,8 MPa. Steam capacity of the steam generator makes possible to produce NPP electric power of 1600 MW.

Figure 6 shows a design version of SG with the economizer. The heat exchanging tube bundle of this SG consists of the evaporator and the economizer connected in parallel over the primary coolant path. Feed water is supplied directly to the specially allocated lower part of the tube bundle central package, not mixing with SG water, passes along the heat exchanging tubes (washing the tubes from the outside), heated to the temperature somewhat below the saturation temperature, and then flows out of the economizer through holes in the upper part of boxes into the volume of evaporating bundle in the area of the primary side “hot” coolant collector.

However, it should be kept in mind that in both cases (WWER-1600 and EPR) it is a matter of design solutions and, to implement them, the studies, justification and run in operation are required. Particularly, in case of arranging the economizer section in PGV-1600 design a number of scientific and engineering problems are to be solved:

- prevention of stagnation zones and local boiling in the heat exchanging tube bundle;
- arrangement of optimal distribution of salt concentration within SG volume;
- assurance of cyclic strength of heat exchanging tubes, as well as their vibration strength and wear-resistance.

In conclusion it should be noted that development of the steam generator design for WWER-1500 RP showed that SG type and dimensions are not the factors limiting the dimensions of RP containment, as it was considered earlier. This conclusion emphasizes the advantages of the horizontal SG and recognizes its application as the perspective way for new RP designs.

CONCLUSION

The horizontal SG showed a rather high reliability and has a number of essential advantages over SGs of other types. The basic trend in activities on improving the reliability of SG for the Units under operation and construction is the meeting of water chemistry requirements at the world level achieved.

Experimental, calculational and theoretical studies of horizontal SGs are a good basis for improving their performance. The SG structure for WWER NPP has high perspectives from the viewpoint of improving the reliability, extending the service life and reducing the maintenance cost. With regard for more stringent requirements for water chemistry and performing the required R&D, the objective is to justify the service life of 50-60 years for new SG designs.

The basic engineering solutions for the operating horizontal SGs can be used for new Units with power up to 1600 MW (el.) that are competitive in the world power market.

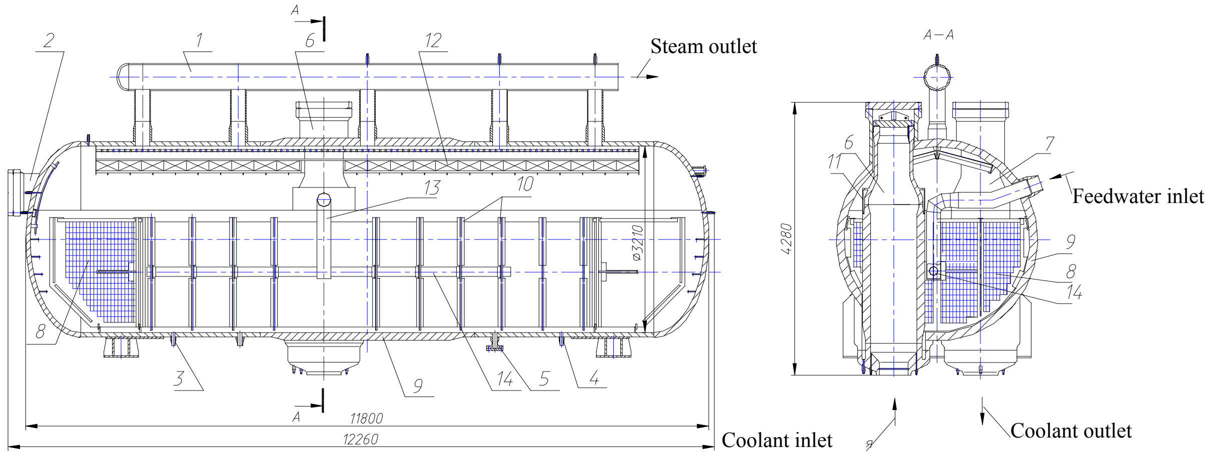

Fig. 1. Structure of steam generator PGV-440:
1 – steam header, 2 – hatch-manhole; 3, 4 – blowdown pipe sleeves; 5 – drainage pipe sleeve; 6, 7 – "hot" and "cold" collectors; 8 – heat exchanging tubes; 9 – steam generator vessel; 10 – heat exchanging tube bundle supports; 11 – protective housing; 12 – separation blinds; 13 – feed water supply tube; 14 – feed water distribution collector

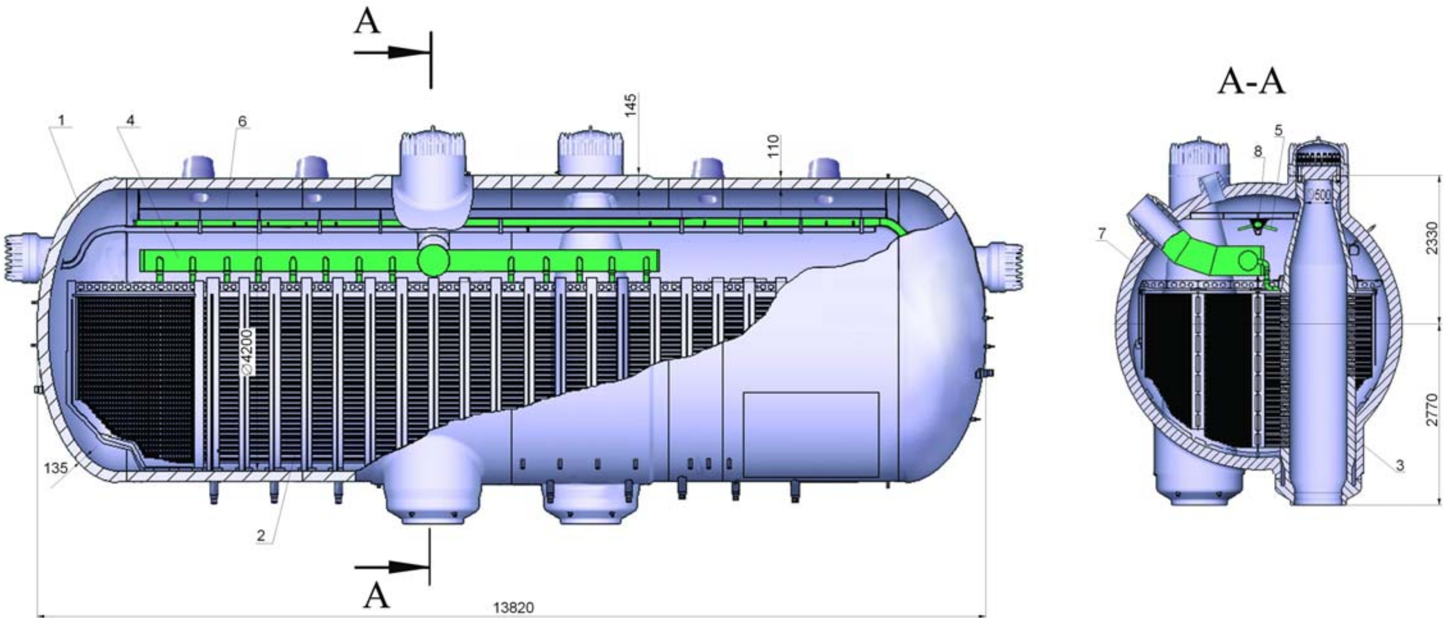

Fig . 2 Steam generator PGV-1000MK with vessel increased diameter and corridor arrangement of heat exchanging tubes in a bundle.

1 – vessel with nozzles of various purposes; 2 – heat exchanging tube bundle with fasteners and spacers; 3 – primary side coolant collector; 4 – device for feed water supply and distribution; 5 – device for feed water supply and distribution under accident conditions; 6 – distribution perforated sheet; 7 – submerged perforated sheet; 8 – device for supply of chemical reagents.

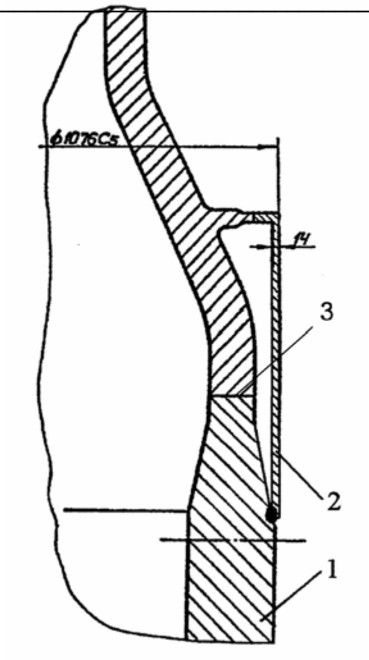

Fig. 3 Housing of the primary side collector of steam generator PGV-4E
1- collector, 2- housing, 3- weld No. 33

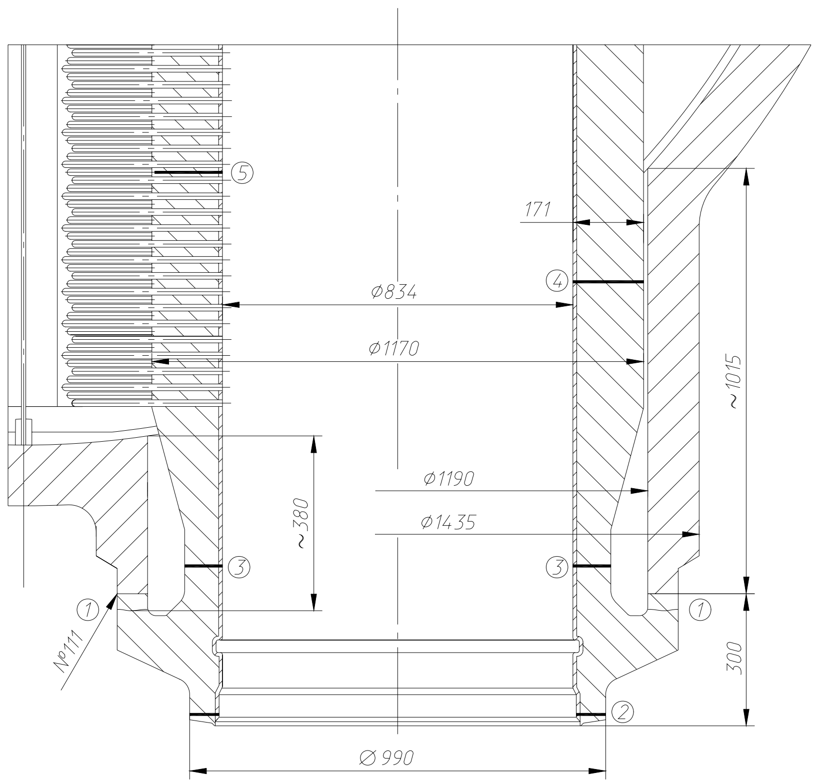

Fig.4 Region of weld No. 111/1

1- A section wherein damages are detected;
2- MCP Dnom 850;
3- Collector ∅834x90;
4- Collector ∅834x171, non-perforated part;
5- Collector ∅834x171, perforated part

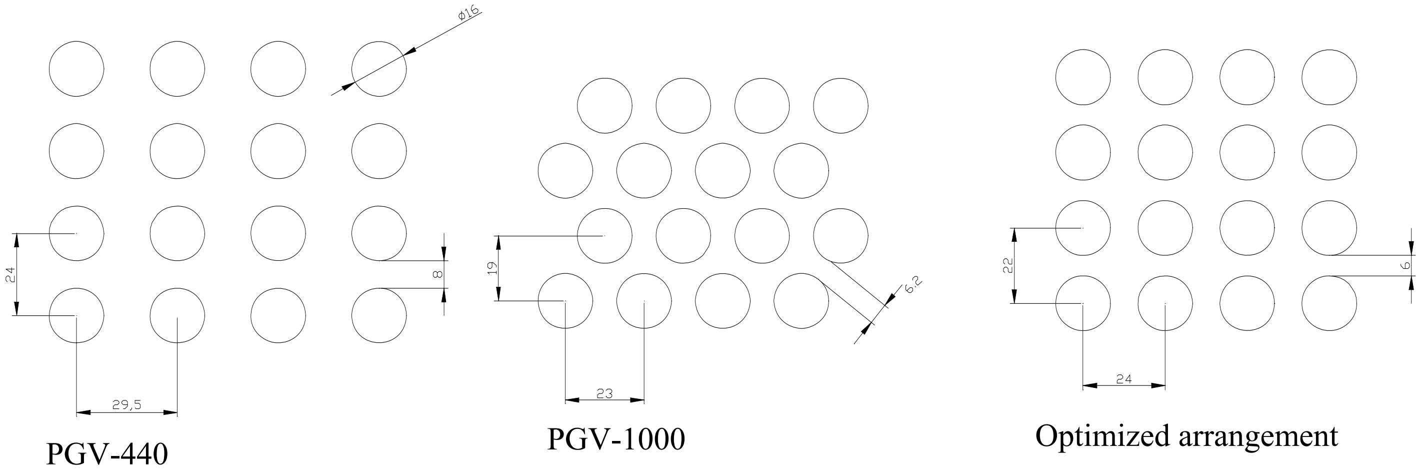

Fig. 5. Arrangements of tube bundles

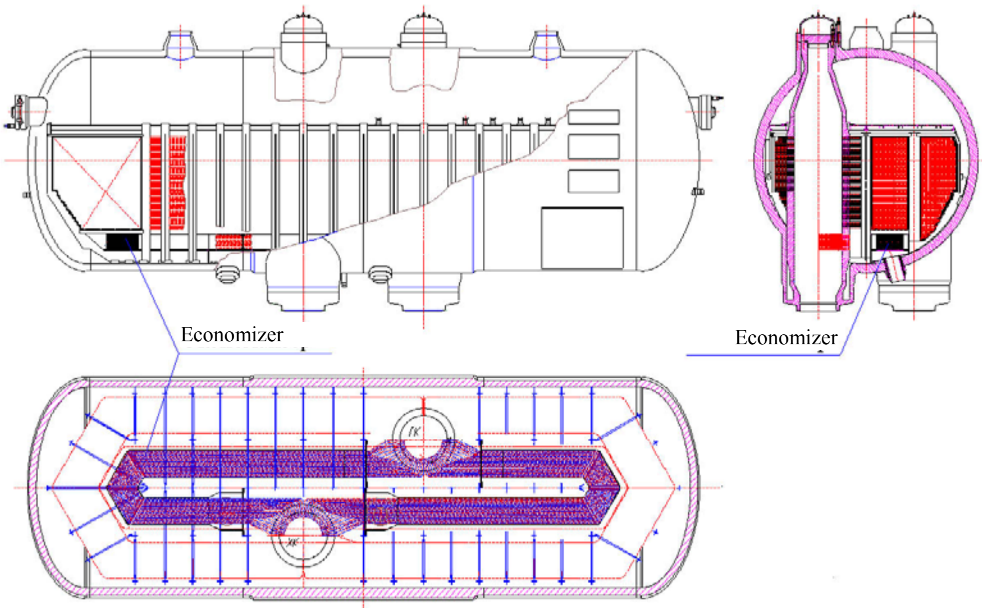

Fig. 6. PGV-1600 with the economizer

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