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Research Article

Components of small and medium sized HLMC reactor plant circuits*

Alexander V. Beznosov[1], Tatyana A. Bokova[1], Pavel A. Bokov[1]

1 *Nizhny Novgorod State Technical University named after R.Ye. Alekseyev, 24 Minina St., Nizhny Novgorod, 603950, Russian Federation*

Corresponding author: *Alexander V. Beznosov* (beznosov@nntu.ru)

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Abstract

Small and medium sized lead and lead-bismuth cooled reactors currently under development in Russia are Generation IV reactors. This paper presents a review and new scientific and engineering solutions which are in line with the evolutionary development of small and medium sized reactor plants with heavy liquid metal coolants (HLMC).

A growing interest in small and medium sized reactor plants for transpolar applications, as well as for regional and other NPPs, and the emerging trend towards the substitution of coal-fired boiler stations for small modular reactors initiate R&D on new designs and operational solutions for fast neutron HLMC reactor plants. Such solutions are based on unique domestic experience of building and operating ground prototype test facilities and series lead-bismuth cooled reactor plants, as well as nuclear power units for various applications. These solutions provide for improved properties of advanced HLMC reactors, primarily in economic and safety terms, as compared to other small and medium sized reactor plants.

Theoretical and experimental work was undertaken at Nizhny Novgorod State Technical University (NNSTU) for justifying small and medium sized reactor plant designs with horizontal steam generators (BRS-GPG). Nonconventional scientific and engineering solutions have been considered aimed to improve the cost effectiveness and safety of HLMC NPP units, including for the localization of a potentially dangerous severe accident of the “intercircuit steam generator break” type. The review and integrated research results are presented which make it possible to justify nonconventional engineering solutions for the BRS-GPG reactor plant (reactor circuit circulation pattern, steam generator type, reactor circuit heat removal in standby and emergency modes, etc.).

Keywords

Small and medium sized reactor plant; key components; engineering solutions; heavy liquid metal coolants; intercircuit SG break

Introduction

A growing interest in small and medium sized reactor plants for transpolar applications, as well as for regional and other NPPs, and the emerging trend towards the substitution of coal-fired boiler stations for small modular reactors initiate R&D on evolutionary and essentially novel designs and operational concepts for facilities with fast neutron HLMC reactors. Such concepts are based on the unique domestic experience of building and operating ground prototype test facilities (27VT, 27VT-5, KM1, a nuclear submarine of design 645) and series reactor

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plants (nuclear submarines of designs 705 and 705K) with lead-bismuth coolants, as well as lead-bismuth and lead cooled nuclear power units (respectively BRS and BREST) for various applications (Beznosov and Bokova 2012). Low near-atmospheric pressure in the reactor circuit (0.1-0.5 MPa), high temperature of the HLMC (up to 500-550 °C) and the generated steam (400-500 °C) with a pressure of 4.0-24.0 MPa, high unit efficiencies (up to 45%), a two-circuit reactor plant arrangement, and use of advanced (nitride) fuel types makes them a reasonable choice for consideration as advanced systems.

HLMC reactor plants are much safer than sodium and water cooled systems and feature a specific stored energy per unit volume 20 times as small as VVER reactor plants and 10 times as small as sodium cooled reactors. HLMC plants have no potential "compression energy", or chemical energy of interaction with zirconium as water, or with water and air as sodium, or potential energy of the hydrogen released with air as water and sodium (Beznosov et al. 2016).

The design justification work and the early development stage are currently under way at NNSTU for a fast neutron lead or lead-bismuth cooled reactor plant of 50 to 250 MWe with horizontal steam generators (BRS-GPG) (Beznosov et al. 2008).

The results of the review and the integrated research undertaken at NNSTU, primarily of the experiments aimed to justify new nonconventional BRS-GPG reactor plant designs (reactor circuit circulation pattern, steam generator type, reactor circuit heat removal in standby and emergency modes, etc.) are presented below.

Coolant selection and justification

Technologies to select, fabricate, assemble and operate lead-bismuth cooled reactor plants have been proven in Russia as applied to the operated pilot nuclear submarine (design 645) and series nuclear submarines (designs 705 and 705K). Lead-bismuth coolant is compatible with water used as fluid in the Rankine cycle. Its melting point of 125 °C corresponds to the steam saturation pressure of 0.23 MPa which makes it possible to remove heat from components containing this coolant with water at a pressure of over 0.3 MPa without its freezing (Beznosov et al. 2006).

This enables the reactor plant cooldown and the heating, where required, of the reactor circuit components by water and steam in standby and emergency modes while preventing the liquid metal coolant from freezing. Such property of the Pb-Bi eutectic improves substantially its consumer qualities. A drawback of lead-bismuth coolant, as compared to lead coolant, is a high Po-210 activity level during the reactor plant operation, which is 20 times higher than in the lead coolant circuit, and the cost of bismuth, an order of magnitude as high as that of lead.

The lead melting temperature of 326 °C corresponds to the saturated steam temperature of about 12.2 MPa. This makes it practically impossible to remove heat from components containing lead coolant with water during the reactor plant cooldown and in standby modes, as a pressure reduction to below this value in the water filled space will cause the lead to freeze with the obstruction of the channel in its lead-containing portion. It is technically difficult and practically impossible to maintain a pressure of above 12.3 MPa inside of steam generators and other heat exchangers during transients or in standby and repair modes, which makes this coolant poorly compatible with water. An extensive experience of operating lead and lead-bismuth cooled test facilities with electrically heated HLMC systems does not show any noticeable difference in their maintenance procedures.

As the reactor coolants, lead and lead-bismuth are practically identical in terms of other characteristics. Based on cost effectiveness and safety criteria, lead coolants appear to be a more reasonable choice than lead-bismuth coolants (Beznosov et al. 2007).

Reactor circuit coolant circulation pattern and reactor unit configuration

The BRS-GPG offers a novel nonconventional reactor circuit and coolant circulation arrangement which minimizes the circuit's length while eliminating the need for additional riser and downcomer portions (Beznosov et al. 2007).

After it flows through the reactor core, the coolant enters the steam generator's superheating section and then its evaporating section, flowing further into the axial-type submersible reactor coolant pump from the discharge end of which it flows down and towards the reactor core inlet (Fig. 1).

Such reactor circuit configuration provides for the maximum possible natural circulation which makes the reactor plant much safer.

Improvement of the reactor safety during a "large sg break" accident

Experiments with relatively large amounts of water, steam and gas (1 kg or more) fed to beneath the free level of the lead and lead-bismuth coolants with the outflow hole being up to 4.0 m below the HLMC level and with a pressure drop of up to 8.0 MPa at the hole through which water and steam enter the HLMC, the HLMC temperature being up to 600 °C, have shown that steam or steam-water mixture form spontaneously a vertical "light-phase" channel between the outflow point to the HLMC free level (dryout) independent of if there is the initial HLMC circulation and notwithstanding its rate, if any (Beznosov et al. 2016a). This result of investigating (simulating) one of the most potentially dangerous HLMC reactor accidents ("large SG break") makes it possible to mitigate in a qua-

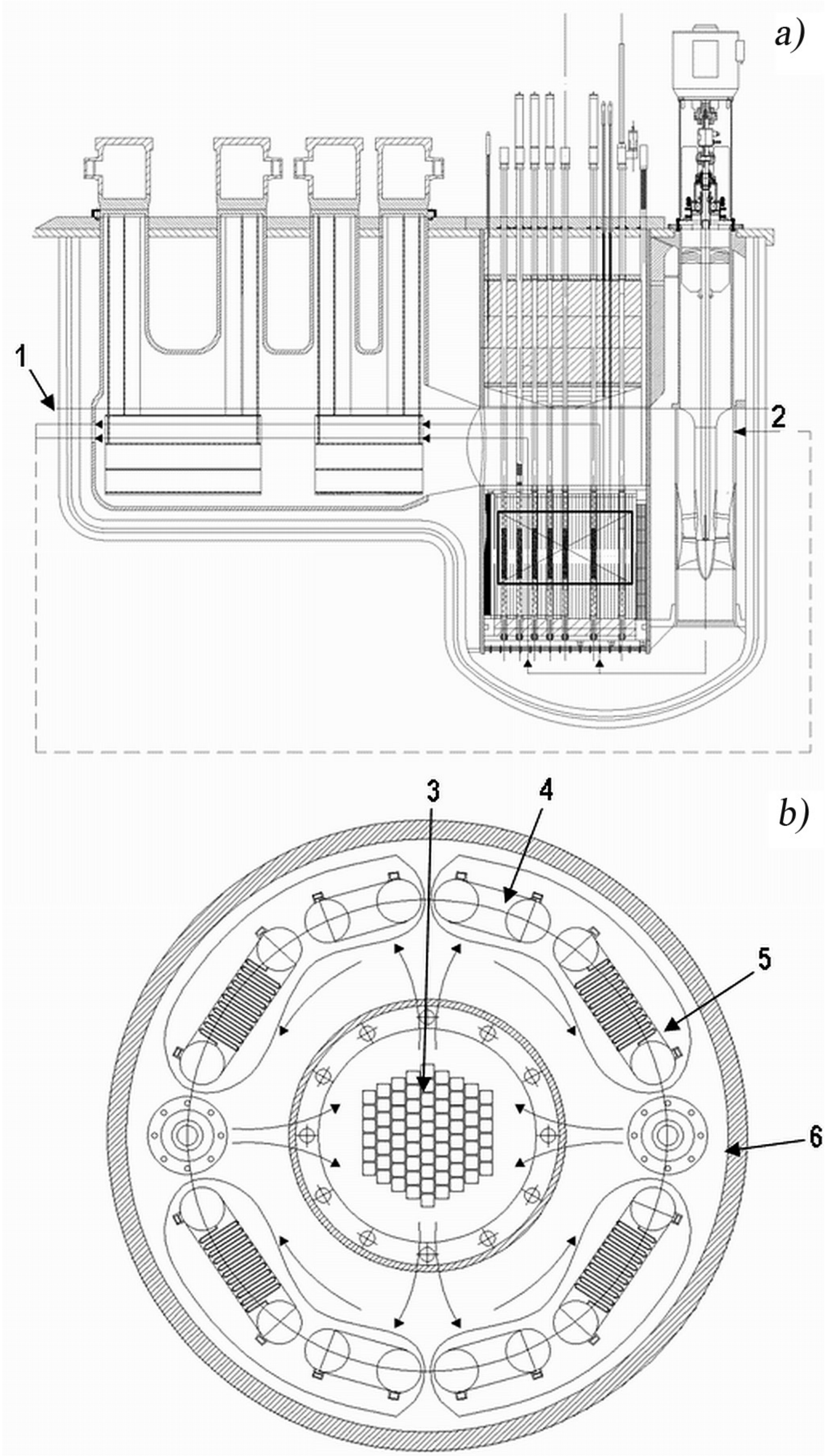

Figure 1. Schematic of the BRS-GPG reactor HLMC circuit: a) sectional drawing; b) top view; 1 – free coolant level; 2 – coolant entering the pump from SG; 3 – core; 4 – horizontal SG's superheating section; 5 – horizontal SG's evaporating section; 6 – RCP$

litative manner the accident effects by using a horizontal steam generator design, the tubes in which are as near as possible to the HLMC level (up to ~ 1.0 m), this preventing water from entering the reactor core and the reactor circuit from being overpressurized, and so on (Beznosov et al. 2013). Such approach, in the event of the SG emergency breakdown ("large break") and with practically the greatest possible fluid emergency outflow rate, provides for the safe localization of an accident with a steam channel formed spontaneously between the fluid outflow point and the gas (steam-gas) space above the free coolant level in the SG's failed section and with the subsequent steam, water and gas escape through the rupture disk and into the condenser, and further to the atmosphere via the condenser and the gas cleaning system (Beznosov et al. 2012a).

Engineering solutions for the steam generator

The optimal BRS-GPG reactor plant design is that with the tubes being at the smallest possible depth below the free HLMC level, e.g. in the form of a system of plate coils with the HLMC flowing about the tubes in the transverse direction and with devices minimizing the coolant stratification. Activities have been undertaken at NNSTU to determine experimentally the heat-exchange characteristics of horizontal tubes when flown about by lead coolant (Iarmonov et al. 2013). In the considered design, the superheating section and the evaporating section may be arranged in the annulus above the reactor core (Beznosov et al. 2008). A peculiarity of the BRS-GPG's SG is that the efficient localization of a "large SG break" accident requires the gas space below the free level in the SG sections to be larger than or equal to the coolant volume in these sections and to communicate with the condenser, e.g. with the bubbler tank having its gas space communicating with the atmosphere via the gas cleaning system, through the rupture disk. For efficiency of operation in conditions of a "small SG break", the gas space of each SG section communicates with the emergency steam condensers and the gas blower.

Engineering solutions for the reactor coolant pump

As applied to the BRS-GPG reactor plant, an axial submersible pump design is proposed with the downward coolant flow (Beznosov et al. 2014). Studies are conducted at NNSTU for the justified BRS-GPG RCP design as part of which the following is determined experimentally in stages:

– key characteristics of the pump impeller cascades defined by the circulation rate as the blades are flown about by the lead coolant with a rate of up to 2000 t/h and a temperature of 450-500 °C, and the best possible impeller design (Bokov et al. 2013);

– the best possible impeller blade profile in the cascade determined at stage 1;

– characteristics and the best possible geometry of the pump inlet and outlet portions, including the vanes.

The NSO-02 NGTU axial electrical pump design (G of up to 2000 t/h, T = 450-500 °C, Pb or Pb-Bi eutectic fluid) has been developed and is being tested at NNSTU for the experimental determination of the optimal impeller blade angles. Where required, the modeled RCP blade rotation can be used to stop the "reverse" current through the RCP in the event of its fault trip in the reactor plant or to minimize the RCP's hydraulic resistance with the HLMC natural circulation in the reactor circuit (Beznosov et al. 2012b).

Reactor cooldown and reactor plant standby modes

High freezing temperature of lead coolant and, to a smaller extent, of lead-bismuth coolant requires special technical approaches to be taken for reliable and safe heat removal in the reactor plant cooldown and standby modes (Beznosov et al. 2002). It is proposed that an air-water mixture with finely dispersed water drops be used in test facilities and in the BRS-GPG reactor plant for the controlled heat removal from the HLMC (Beznosov et al. 2015). The amount of the removed heat is efficiently controlled by varying the water content in the two-component flow based on sensor signals and the heat exchanger outlet temperature (Beznosov et al. 2014a). The characteristics of such system are studied and optimized at NNSTU's test facilities, including the FT-4 NGTU test facility for the removal of the heat produced by the BREST-OD-300 reactor RCP model's electrical pump (Beznosov et al. 2008a). It is considered for the BRS-GPG that self-contained air-to-water heat exchangers should be installed inside of the SG or the SG evaporator surfaces should be used in air-to-water modes (Beznosov et al. 2016b).

Peculiarities of the structural material operation in the BRS-GPG HLMC

In the process of the HLMC reactor plant operation, the structural material (steel) contacts, through the protective film (oxide or, possibly, of another type) formed on its surface for keeping it serviceable at $T \geq$ 400-450 °C, as well as through the wall layer the characteristics of which are defined by the impurity mass exchange and mass transport processes both in the circuit and in its locally considered length (Beznosov et al. 2012b).

The wall layer, as has been shown by direct experiments (Beznosov et al. 2012b), is a dispersed system with surface properties composed of a liquid metal coolant (liquid phase) and impurity particles (solid phase in the form of oxides and other coolant compounds, steel components and their compounds, etc.).

With regard for this, it is proposed that the resistance of the BRS-GPG reactor circuit structural materials be determined in conditions of their contact, including thermal and hydrodynamic contact, with the wall layer and the HLMC in a particular circuit length. Serviceability of ferrite-martensite and austenitic chromium-nickel steels has been currently justified as applied to the BRS-GPG reactor circuit conditions with the HLMC containing 10^{-4} – 10^{-2} of thermodynamically active oxygen, this providing for the formation and additional formation of respective protective films on the steel surfaces (Beznosov et al. 2010, Beznosov et al. 2005, Beznosov et al. 2014).

Heavy liquid metal coolant technology

A number of sensors are proposed to be installed in the reactor circuit to enable online monitoring of the oxygen thermodynamic activity in the HLMC. Based on respective signals from these sensors, the circuit will be monitored and serviceability of the protective oxide films will be ensured based on monitoring data by the introduction of oxygen in any form (gaseous oxygen, etc.). It is proposed that the coolant and the circuits will be cleaned of the coolant oxides using water-containing gas mixtures based on the sensor signals. Operations for the online monitoring and control of the oxygen content in the HLMC and in the reactor circuit have been perfectly well optimized in test bench conditions and in transport reactor plants (Beznosov et al. 2010).

A gas mass exchanger, a novel nonconventional device, is proposed as an option of the HLMC oxygen content control devices for maintaining the protective oxide films and for the circuit cleaning of the HLMC oxides in the BRS-GPG (Beznosov et al. 2008b). This device, based on respective activity meter signals, introduces a finely dispersed gas phase (a recovery phase, that is, in a mixture with hydrogen, or an oxidizing phase, that is, in a mixture with oxygen) into the volume and further into the liquid metal coolant flow thanks to the entrainment of small gas bubbles by the HLMC jets coming onto the free surface of the coolant at the point of its entry into the RCP. The finely dispersed gas phase composed of a two-component flow enters the core downstream of the RCP and further the SG sections. Such mass exchanger was studied at the HLMC test facilities at NNSTU and was used as the standard device in the facility for testing and optimizing the BREST-OD-300 RCP flow path models (at the FT-4 NGTU test facility) with a nominal lead coolant flow rate of up to 2000 t/h (Beznosov et al. 2005).

Conclusion

Novel technical concepts have been proposed and considered for small and medium sized liquid metal cooled reactor circuits for the purpose of improving their safety and cost effectiveness.

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