UDC 621.039

V. Kovalchuk, PhD, Assoc. Prof.,
I. Kozlov, DSc., Prof.,
O. Chulkin, PhD, Assoc. Prof.,
K. Karchev,
V. Miliev
Odessa Polytechnic National University, Shevchenko Ave. 1, Odesa, Ukraine, 65044; e mail: kozlov_i.l_@ukr.net

ASSESSMENT OF STABILITY OF NATURAL CIRCULATION IN THE FIRST CIRCUIT OF SMALL MODULAR REACTORS

В. Ковальчук, І. Козлов, О. Чулкін, К. Карчев, В. Мілєв. **Оцінка стійкості природної циркуляції у першому контурі малих модульних реакторів.** Робота містить результати дослідження питання впливу архітектури та робочих параметрів водоводяної модульної реакторної установки на її функціонування в режимі природної циркуляції теплоносія першого контуру. Метою дослідження є оцінка можливості організації режиму природної циркуляції в першому контурі модульного реактора із заданими структурою, геометрією та тепловими показниками. У світі на різних етапах розробки перебуває понад 50 проектів реакторів малої потужності, призначених для задоволення енергетичних потреб регіонів різного рівня ресурсозабезпеченості. До передбачуваних переваг модульних конструкцій, поряд з можливістю їхнього серійного виробництва, відносять гнучкість режимів експлуатації та підвищену безпеку, обумовлену застосуванням природної циркуляції теплоносія в першому контурі. Методологія базується на класичних принципах балансу сил, що діють на систему, в стаціонарному стані, якою є замкнутий контур реакторної установки в процесі експлуатації. Необхідні характеристики компонентів контуру (реактора та парогенератора) отримані в результаті їх розрахунків стосовно вибраного базового модуля SMR 160. Технологічна структура енергетичного об'єкта отримана масштабним аналізом ілюстративних матеріалів. Порівняння розрахункових значень рушійного напору (19412 Па) та сумарних втрат у контурі (27302 Па) показало, що для організації стійкого режиму природної циркуляції необхідно шляхом спільної варіації параметрів архітектури та режимних характеристик контуру оптимізувати структуру установки, що забезпечує гнучкі режими експлуатації. Результати дослідження підтвердили доцільність застосування принципу балансу діючих сил з метою оцінки можливості організації природної циркуляції у замкнутому контурі. У роботі запропоновано методику передпроєктного спільного аналізу архітектури енергетичного модуля та його робочих параметрів для забезпечення надійної та безпечної експлуатації ядерної установки в автономних умовах.
Ключові слова: модульні реактори, природна циркуляція, режим експлуатації, рушійний напір, гідравлічний опір, контур циркуляції

V. Kovalchuk, I. Kozlov, O. Chulkin, K. Karchev, V. Miliev. **Assessment of stability of natural circulation in the first circuit of small modular reactors.** The work contains the results of the study of the influence of the architecture and operating parameters of the water-based modular reactor plant on its functioning in the mode of natural circulation of the coolant of the first circuit. The purpose of the study is to assess the possibility of organizing a natural circulation regime in the first circuit of a modular reactor with the given structure, geometry and thermal parameters. In the world, there are more than 50 low-power reactor projects at various stages of development, designed to meet the energy needs of regions with different levels of resource availability. The expected advantages of modular designs, along with the possibility of their serial production, include the flexibility of operating modes and increased safety due to the use of natural circulation of the coolant in the first circuit. The methodology is based on the classical principles of the balance of forces acting on the system in a steady state, which is the closed loop of the reactor plant during operation. The necessary characteristics of the circuit components (reactor and steam generator) were obtained as a result of their calculations for the selected basic module SMR 160. The technological structure of the energy facility was obtained by a large-scale analysis of illustrative materials. Comparison of the calculated values of the driving pressure (19412 Pa) and total losses in the circuit (27302 Pa) showed that to organize a stable natural circulation mode, it is necessary to optimize the structure of the installation by jointly varying the parameters of the architecture and the operating characteristics of the circuit, which ensures flexible operating modes. The results of the study confirmed the feasibility of applying the principle of balance of forces to assess the possibility of organizing natural circulation in a closed loop. The paper proposes a methodology for pre-design joint analysis of the architecture of the power module and its operating parameters to ensure reliable and safe operation of a nuclear facility in autonomous conditions.
Keywords: modular reactors, natural circulation, operating mode, driving pressure, hydraulic resistance, circulation circuit

Introduction

The last two decades have been characterized by close attention to the development of new technologies that contribute to overcoming the problems of optimal supply of regions with vital resources. An important position in this direction is nuclear energy. Developers of new reactor technologies claim that the future of nuclear power lies in small modular reactors (SMR), which have a number of advantages over large-capacity power units. More than 50 projects of low-power reactors are in various stages of development in the world [1].

Interest in them is due to a number of expected advantages: modular design, serial production of power units, operational flexibility and increased safety. This is due to the use of natural circulation of the coolant in the first circuit.

DOI: 10.15276/opu.2.70.2024.07

ISSN 2076-2429 (print)
ISSN 2223-3814 (online)

Analysis of the state of the problem

In water-water type reactors, the circulation of the coolant is usually carried out forcibly. Of great practical interest is the possibility of reactor operation with natural coolant circulation (NCC), which is especially important for emergency (in case of cessation of coolant supply to the active zone by the pump) and regular cooling modes, as well as power increase [2, 3].

In some SMR projects, the principle of natural circulation is expected to be applied. For example, in the CAREM-25 (Argentina) and NuScale (USA) projects, in normal operation mode, full natural circulation of the coolant of the first circuit is used in the absence of main circulation pumps [4].

Natural circulation is understood as the ability of the liquid to circulate continuously in the system under the action of a single driving force – "thermal pressure", which occurs when the density of the heat carrier changes under the influence of the introduction and removal of thermal energy in the circuit. A liquid system intended for natural circulation must have a heat source and a heat sink, which can be used as an active zone and a steam generator, respectively.

In reactors operating on the principle of natural circulation, the combination of neutron-physical and thermo-hydraulic phenomena is important. As part of the joint efforts of the IAEA to promote international cooperation aimed at improving the safety of nuclear power plants, a program was implemented to develop methods for evaluating the operation of the passive safety system in advanced reactors, which notes the advantages and disadvantages of natural circulation systems (Table 1), [5].

Table 1

Advantages and disadvantages of natural circulation systems

Advantages	Disadvantages
The lowest cost due to simplicity	Low driving force
Lack of pumps	Lower maximum power in each channel
The possibility of improving the current distribution in the active zone	Potential instability
The best two-phase characteristics depending on the power	Low critical heat flux
Great thermal inertia	The need for complex start-up procedures

The possibility of providing several passive systems based on the principle of natural circulation, in addition to active systems, is considered in the operated nuclear reactors. This will not only increase the operational safety of reactors, but also prevent hypothetical severe accidents.

One of the possible emergency situations that can occur during the operation of NPP power units is the main circulation pumps (MCP). In such situations, emergency shutdown of the reactor and closure of the turbine stop-control valves are required. The reactor itself is then transferred to the natural coolant circulation mode (NCC) in the primary circuit, which will ensure the release of excess energy during the process of refrigeration. With normal parameters of the coolant at the entrance to the reactor after shutdown (t_{in}=288 °C), it is possible to ensure the removal of thermal power from the reactor plant, which does not exceed 7…10% of the nominal one, which is quite enough to ensure reliable cooling of the reactor [3]. It is expedient to increase the heat output from the reactor in the mode of natural circulation of the coolant in order to ensure the operation of the power unit when the main circulation pump is de-energized in the energy mode (albeit at a reduced power level) with the delivery of electricity to the network [3].

The April 2023 agreement between Energoatom NAEC and Holtec International (USA) envisages the construction of up to 20 nuclear power units with SMR-160 reactors in Ukraine, with the implementation of the first pilot project and reaching the minimum regulated power of the reactor and connecting to the grid by March 2029 year. Therefore, the above-mentioned module was chosen as the object of research.

The purpose and objectives of the research

The purpose of the presented material is to assess the possibility of organizing a natural circulation regime in the first circuit of a modular reactor with the given structure and thermal parameters.

To achieve the goal, it is necessary to solve the following tasks:

– Obtaining the geometric structure of the first contour of the selected module;

– Obtaining the calculated structural and technological indicators of the elements of the first circuit of the selected module;

– Calculation of thermohydraulic parameters of the coolant in the circuit.

Object and method of research

The Holtec SMR-160 modular reactor is a non-boiling, pressurized light water (PWR) system. Electric power 160 MW, thermal power – 525 MW [6].

The first circuit is supposed to be implemented in the form of a monoblock, which includes a rigidly connected reactor and a steam generator. A lead is made from the space above the active zone, which runs along the axis of the steam generator to its upper inlet chamber, where the flow is expanded and distributed through the heat exchange pipes. Further, the flow is collected in the lower chamber of the steam generator and enters the space around the active zone through the annular pipeline (Fig. 1). The natural circulation of the coolant is carried out under the influence of thermal pressure between the rising and lowering channels of the circuit.

The characteristics of the reactor and steam generator necessary for the analysis were obtained in previously performed thermohydraulic calculations (Tables 2, 3, 4) [7, 8, 9].

A large-scale analysis of the illustrations accompanying the available descriptions of the module created a table of heights of individual elements of the module (Table 2).

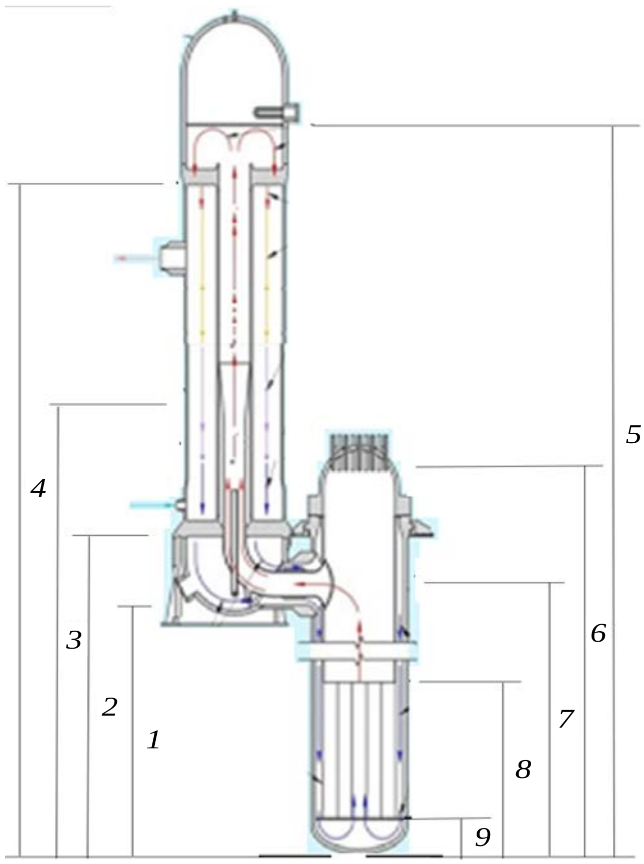

Fig. 1. Diagram 1 of the circuit of the module: *1* – The lower limit of the output chamber of the steam generator; *2* – Lower pipe board; *3* – Border of economizer and evaporation areas; *4* – Upper pipe board; *5* – Pressure compensator membrane; *6* – The upper level of the space above the active zone; *7* – The level of removal from the space above the active zone to the steam generator; *8* – Upper level of the active zone; *9* – The lower level of the active zone

Table 2

Limit heights of monoblock elements

№	Levels	Height, m
1	The lower limit of the collecting chamber	9.9
2	The lower grill of the steam generator	13.3
3	Border economizer-evaporator	13.3
4	The upper grid of the steam generator	33
5	Compensator membranes	35
6	The upper limit of the supra reactor space	13.8
7	Discharge to the riser area, which is not heated	9.9
8	The upper limit of the active zone	2.7
9	The lower limit of the active zone	0.6

In order to assess the possibility of implementing circulation, as well as the safety and reliability of the module operation, a comparison of the calculated thermohydraulic modes and the spatial structure of the circuit was made.

The condition for the stability of the stationary mode of natural circulation in a closed circuit is the equality of the driving pressure Δp_{mp} and the hydraulic resistance Δp_{hr} of the circuit [10, 11].

The moving pressure Δp_{mp} is directly proportional to the difference in the densities of the heat carrier in the rising (“hot” ρ_h) and lowering (“cold” ρ_c) sections of the circulation circuit and the difference ΔH of the height marks of the sections with heat supply (active zone) and removal (steam generator):

 ISSN 2076-2429 (print)
ISSN 2223-3814 (online)

$$\Delta p_{\text{mp}} = g(\rho_c - \rho_h)\Delta H\ , \tag{1}$$

the hydraulic resistance Δp_{mp} is proportional to the square of the flow G_i of the coolant through the circuit:

$$\Delta p_{\text{hr}} = \sum_{i=1}^{n} \xi_i \frac{G_i^2}{2\rho_i F_i^2}\ , \tag{2}$$

where ξ_i – coefficient of resistance;

ρ_i – is the density of the heat carrier;

F_i is the area of the circuit section.

Taking into account (1, 2), the condition for the stability of the natural circulation regime takes the form:

$$g(\rho_{\text{c}} - \rho_{\text{h}})\Delta H = \sum_{i=1}^{n} \xi \frac{G_i^2}{2\rho_i F_i^2}\ , \tag{3}$$

where g – acceleration of free fall, m/s^2;

ρ_x, ρ_g – heat carrier density in the rising and lowering sections of the main circulation circuit (MCC), kg/m^3;

ΔH – the difference in height between the centers of the heat exchange surface of the steam generator and the active zone of the reactor, m;

ξ_i – coefficient of hydraulic resistance of the ith section of the MCC;

G_i, ρ_i – flow rate (kg/s) and heat carrier density (kg/m^3) at the i_{th} section of the MCC;

F_i – the area of the cross-section of the *i*-th section of the MCC, m^2.

Table 3

Calculation characteristics of the active zone

Characteristics	Designation	Units of measurement.	Value under load		
Average specific volumetric load,	N_υ^{AV}	MW/m^3	65	85	100
Heat capacity	N_{H}	MW	525	525	525
The density of the coolant under operating parameters	ρ_{az}	kg/m^3	758.7	758.7	758.7
Volume of the active zone	V_{az}	m^3	8.6	6.6	5.6
The diameter of the active zone	D_{az}	m	2.33	2.13	2.02
The height of the active zone	H_{az}	m	2.03	1.85	1.76
Speed required for heat removal	w_{az}	m/s	0.64	0.77	0.86
Number of fuel assemblies	N_{as}	piece	53	58	61
Leveling component of hydraulic resistance	Δp_{l}	kPa	13.8	12.6	11.9
Hydraulic friction losses	Δp_{f}	kPa	0.37	0.47	0.54
Hydraulic losses from local resistances	Δp_{lr}	kPa	0.60	0.86	0.92
Coolant pressure losses in a medium-loaded cell	Δp_{Σ}	kP	14.7	13.9	13.4

To estimate the maximum driving pressure in the circuit with natural circulation according to the ratio (1), the difference in height marks between the centers of the heat exchange surface of the steam generator and the active zone of the reactor is necessary.

Active forces at the entrance to the active zone:

– from the side of the down channel,

$$F_0 = g\rho_{\text{sg}}^{\text{c}}\Delta H_{\text{sg}} + gH_2 \cdot \rho_{\text{sg}}^{\text{esg}} - \Delta p_0\ ; \tag{4}$$

– from the side of the lifting channel,

$$F_L = g(\rho_{\text{sg}}^{\text{c}}\Delta H_{sg} + (H_5 - H_8)\rho_{\text{sg}}^{\text{esg}}) + \Delta p_l\ , \tag{5}$$

where $\rho_{\text{sg}}^{\text{c}}$ – the density of the heat carrier in the center of the heat exchange surface of the steam generator;

ΔH_{sg} is the height of the heat exchange surface of the steam generator;

ρ_{sg}^{esg} – the density of the heat carrier at the exit from the steam generator;

ΔH_2 – the height of the lower boundary of the heat exchange surface of the steam generator;

Δp_0 – the sum of the hydraulic losses in the lowering channel;

$(H_5–H_8)$ is the height of the section of the lifting channel that is not heated;

Δp_l is the sum of hydraulic losses in the lifting channel.

Table 4

Calculation characteristics of the steam generator

Characteristics	Designation	Units of measurement	Values at the speed of the coolant		
heat carrier flow through the first circuit through the steam generator	G_{HC}	kg/s	1479	1479	1479
heat capacity of the evaporator	N_{HE}	MW	443.4	443.4	443.4
thermal capacity of the economizer	N_{TE}		81.63	81.63	81.63
coolant speed	w_{HC}	MW	1	1,6	2.6
the number of tubes on the surface	n_{NT}	m/s	22540	14080	8667
Number of steam generator modules	n_{MSG}	piece	8/2817	8/1761	8/1083
heat exchange surface of the evaporator	S_{EV}	piece	1439	1119	884
the length of the tube of the evaporation section	$L_{B\Pi}$	m^2	13.01	16.19	20.78
average speed	$w_{B\Pi}$	m	0.89	1.43	2.32
heat exchange surface of the economizer	S_{EK}	m/s	127	101	82
the length of the tube of the economizer section	L_{EK}	m^2	1.03	1.3	1.72
total calculated heat exchange area	S_{HE}	m	1566	1219	965
with a margin	S_{HEm}	m^2	1801	1402	1110
the total length of the tube, taking into account the margin factor	L_{HEm}	m	16.34	20.36	26.19
hydraulic losses due to friction	Δp_f	m	16467	52513	178407
turn 90 degrees	Ξ_l	Pa	0.2	0.2	0.2
entrance to the tubes from the distribution chamber	Ξ_l	–	0.5	0.5	0.5
exit to the assembly chamber	Ξ_l	–	1.0	1.0	1.0
entrance to the outlet pipe from the collector	Ξ_l	–	0.5	0.5	0.5
hydraulic losses on local supports	Δp_{ls}	–	825	2112	5577
hydraulic resistance of the first circuit	Δp_{hr}	Pa	17292	54625	183984

Equality of forces in any section of the circuit ensures a stationary mode of natural circulation:

$$g(\rho_{sg}^{c}\Delta H_{sg} + H_2\rho_{sg}^{esg}) - \Delta p_l = \\ = g(\rho_{az}^{c}\Delta H_{az} + (H_5 - H_8)\rho_{az}^{ef}) + \Delta p_0 + \Delta p_{Fr}, \qquad (6)$$

where ρ_{az}^{c} – the density of the heat carrier in the center of the heat exchange surface of the active zone;

ΔH – the height of the heat exchange surface of the active zone;

ρ_{az}^{ef} – the density of the heat carrier at the exit from the active zone;

Head loss in the circuit, caused by the switching features of the steam generator and the active zone, which takes into account the indicator of hydraulic losses due to friction Δp_{Fr}.

After transforming (6) into form (7):

$$g(\rho_{sg}^{c}H_{sg} + H_2\rho_{sg}^{esg} - \rho_{az}^{c}H_{az} - (H_5 - H_8)\rho_{az}^{ef}) = \Delta p_l + \Delta p_0 + \Delta p_{Fr}, \qquad (7),$$

ISSN 2076-2429 (print)
ISSN 2223-3814 (online)

we will get an expression, the left part of which reflects the effective heat pressure, and the right part – the sum of hydraulic losses in the circuit.

The results of the research

Substitution of data from Tables 2, 3 and 4 allows you to obtain the result of checking the condition of the existence of a stationary mode of natural circulation:

$$9.81(758.73(33-13.3)+13.3\cdot 825.42-758.73(2.7-0.6)-(35-2.7)692.04)=13923.15+9949.38;$$

$$\text{thrust}\Rightarrow 19.412\,\text{kPa}=t\text{otal losses}\Rightarrow 23.872\,\text{kPa}.$$

The calculated driving pressure was 19412 Pa, and the total losses in the circuit reach 27302 Pa. With the obtained ratio of driving pressure and losses, the occurrence of natural circulation is excluded. It follows from (7) that with unchanged thermo-hydraulic parameters, the ratio of head and losses depends on the difference in the height of the average temperatures in the rising and lowering channels, which are constructively determined by the values of H_2 and H_5. Variations of their values showed that an increase in the values accepted in the calculation by 2.7…2.8 m allows to achieve the necessary balance of driving pressure (27302 Pa) and losses (27302 Pa), and, therefore, to realize the mode of natural circulation. The size of the variation does not exceed 7% of the total height of the block and can be attributed to the inaccuracies of the illustrative material used in the large-scale analysis.

Conclusions

– The geometric structure of the first contour of the Holtec SMR-160 module was obtained by large-scale analysis of existing illustrations;

– The structural and technological indicators of the active zone, steam generator and switching elements of the first circuit of the Holtec SMR-160 module were obtained;

– The thermal-hydraulic parameters of the coolant in the circuit were calculated and analyzed. It has been proven that the chosen architecture of the circuit allows to organize a stable mode of natural circulation in the circuit of the SMR 160 modular reactor.

Література

1. Чорний В.С., Олійник Ю.О., Тептя В.В. ПЕРСПЕКТИВИ РОЗВИТКУ МОДУЛЬНИХ РЕАКТОРІВ. *Вінницький національний технічний університет*. 2024. URL: https://conferences.vntu.edu.ua/index.php/mn/mn2024/paper/viewFile/19113/15844.
2. Лавренчук А.Ю., Мирошниченко С.Т., Герлига В.А., Шевелев Д.В. Оценка устойчивости алгоритмов автоматического регулирования расхода действующих САОЗ ВД реакторов ВВЭР в случае естественной циркуляции теплоносителя. *Збірник наукових праць СНУЯЕ та П.* 2013. С. 13–21.
3. Ильченко А.Г., Зуев А.Н., Харитонин И.Е., Исследование работы энергоблока ВВЭР-1000 в режиме естественной циркуляции теплоносителя. *Вестник ИГЭУ*. 2008. Вып 2. С. 1–5.
4. Zabulonov Yu.L. Prospects for the implementation of small modular reactors in Ukraine. *Visn. Nac. Akad. Nauk Ukr.* 2023. (6). 34–46. DOI : https://doi.org/10.15407/visn2023.06.034.
5. Комаров Ю.А. Развитие риск-ориентированных подходов для повышения безопасности и эффективности эксплуатации атомных электростанций: монография / Под ред. В. И. Скалозубова., Чернобыль : НАН Украины, Ин-т проблем безопасности АЭС, 2014. 288 с. URL: https://www.ispnpp.kiev.ua › komarov-2014.
6. Малогулко Ю.В., Сліденко М.О. Перспективи впровадження технологій використання малих модульних реакторів. *Вінницький національний технічний університет*. 2020. URL: https://ir.lib.vntu.edu.ua/bitstream/handle/123456789/42136/19751.pdf?sequence=3&isAllowed=y.
7. Карими Дж., Шаестех М., Занджиан М. Расчет активной зоны малого модульного реактора АБВ во время цикла выгорания. *Атомная техника за рубежом.* 2021. № 4. С. 22–31.
8. Реактори і парогенератори енергоблоків АЕС: схеми, процеси, матеріали, конструкції, моделі / О. В. Єфімов, М. М. Пилипенко, Т. В. Потаніна та ін. / за ред. О.В. Єфімова. Харків : ТОВ «В справі», 2017. 420 с.
9. Increasing the Efficiency and Level of Environmental Safety of Pro-Environmental City Heat Supply Technologies by Low Power Nuclear Plants / V. Kravchenko, I. Kozlov, V. Vashchenko, I. Korduba, A. Overchenko, S. Tsybytovskyi. *World Journal of Nuclear Science and Technology.* 2024. Vol. 14 № 2. P 107–117. DOI: 10.4236/wjnst.2024.142006.
10. Федоров Л.Ф., Рассохин Н.Г. Процессы генерации пара на атомных электростанциях. М. : Энергоатомиздат, 1985. 288 с.

11. Логинова С.С. Исследование устойчивости контура естественной циркуляции теплоносителя. *Вестник науки и образования.* 2017. №7, Том 31. С. 5–7.

References

1. Chornyi, V.S., Oliynyk, Yu.O., & Teptya, V.V. (2024). PROSPECTS FOR THE DEVELOPMENT OF MODULAR REACTORS. Vinnytsia National Technical University. Retrieved from: https://conferences.vntu.edu.ua/index.php/mn/mn2024/paper/viewFile/19113/15844.
2. Lavrenchuk, A.Yu., Myroshnychenko, S.T., Gerlyga, V.A., & Shevelev, D.V. (2013). Evaluation of the stability of algorithms for automatic regulation of the flow rate of the operating SAOZ VD reactors of VVER in the case of natural circulation of the coolant. *Collection of scientific works of the SNUYAE and P*, 13–21.
3. Ilchenko, A.G., Zuev, A.N., & Kharitonin, I.E., (2008). Study of WWER-1000 power unit operation in natural coolant circulation mode. *ISU Bulletin*, 2. 1–5.
4. Zabulonov, Yu.L. (2023). Prospects for the implementation of small modular reactors in Ukraine. *Visn. Nac. Akad. Nauk Ukr.* 6, 34–46. Retrieved from: https://doi.org/10.15407/visn2023.06.034.
5. Komarov, Yu.A., & Skalozubov, V.I. ed. (2014). *Development of risk-oriented approaches to increase safety and efficiency of operation of nuclear power plants*: monograph, Chernobyl: National Academy of Sciences of Ukraine, Institute of NPP Safety Problems, 2014. 288 p. URL: https://www.ispnpp.kiev.ua › komarov-2014.
6. Malogulko, Y.V., & Slidenko, M.O. (2020). Prospects for the introduction of technologies for the use of small modular reactors. *Vinnytsia National Technical University.* URL: https://ir.lib.vntu.edu.ua/bitstream/handle/123456789/42136/19751.pdf?sequence=3&isAllowed=y.
7. Karimy, J., Shaesteh, M., & Zandjian, M. (2021). Calculation of the active zone of a small modular ABV reactor during the burn-up cycle. *Nuclear technology abroad*, 4, 22–31.
8. Yefimov, O.V., Pylypenko, M.M., & Potanina, T.V. et al. (2017). *Reactors and steam generators of nuclear power units: schemes, processes, materials, designs, models.* In: O.V. Yefimov, ed. Kharkiv: LLC In the case.
9. Kravchenko, V., Kozlov, I., Vashchenko, V., Korduba, I., Overchenko, A., & Tsybytovskyi, S. (2024). Increasing the Efficiency and Level of Environmental Safety of Pro-Environmental City Heat Supply Technologies by Low Power Nuclear Plants. *World Journal of Nuclear Science and Technology*, 14, 107–117. DOI: 10.4236/wjnst.2024.142006.
10. Fedorov, L.F., & Rassokhin, N.G. (1985). *Processes of steam generation at nuclear power plants*. M.: Energoatomizdat.
11. Loginova, S.S. (2017). Study of stability of the natural circulation circuit of the coolant. *Bulletin of Science and Education*, 7, 31, 5–7.

Ковальчук Вячеслав Іванович; Vyacheslav Kovalchuk, https://orcid.org/0000-0001-8696-4414
Козлов Ігор Леонідович; Igor Kozlov, ORCID: http://orcid.org/0000-0003-0435-6373
Чулкін Олег Олексадрович; Oleg Chulkin, ORCID: http://orcid.org/0000-0001-5048-4515
Карчев Костянтин Дмитрович; Konstantin Karchev, ORCID: https://orcid.org/0000-0002-2666-1814
Мілєв Вячеслав Петрович; Viacheslav Miliev, ORCID: http://orcid.org/0009-0000-2289-2490

Received October 01, 2024

Accepted November 27, 2024