UTILIZATION OF HTGR HEAT AND ITS TRANSFER TO INDUSTRIAL FACILITIES

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Abstract

Heat utilization of a modular helium cooled reactor with the temperature of 750-900°C, which can not be attained by other reactor types, and with high level of safety is considered. Requirements of the heat power value and maneuverability of the industrial processes, to which a nuclear reactor is to be integrated, are discussed on an example of a standard oil refinery plant. Heat removal systems from the reactor block to industrial processes are analyzed from a safety, economy and maneuverability point of view. Selection and requirements for the intermediate coolant are also discussed.

1. INTRODUCTION

Oil refinery industry is one of the most energy-consuming sectors in the national economy, spending up to 20% of extracted oil [1]. This fact itself confirms the grounds why using nuclear energy in industry processes is economically expedient in addition to advantages in ecology, transport expenditures etc.

Especially it relates to reactor plants (RP) with high temperature gas cooled reactors (HTGR) having an outlet helium temperature of up to 950°C. In OKB Mechanical Engineering the design of a pilot-industrial modular reactor plant VGM has been developed [2]. Based on this concept industrial RPs are being designed for supplying industrial processes with heat in a wide temperature range (up to 900°C) which can not be provided by other reactor types.

Nuclear power process stations (NPPS) with an HTGR can provide all existing and perspective technologies with heat of required temperature level:

- high temperature processes (up to 950°) for the production of petroleum products and diesel fuel from coal, for the production of hydrogen, ammonia and mineral fertilizers by methane steam conversion, etc.;
- middle temperature processes (up to 600 °C) for mainly the secondary reprocessing of the oil products - reforming , cracking, etc.; and
- low temperature processes (up to 400 °C) for mainly the initial reprocessing of the oil products - hydrocracking, hydrocleaning and centralized district heating, etc.

2. MAIN REQUIREMENTS FOR A NUCLEAR POWER PROCESS STATION SPECIFIED BY THE OIL REFINERY PLANT

Most processes in all the temperature ranges mentioned above are existing at the oil refinery plants (ORPs). In order to specify requirements for the ORP and the heat consumption depending on process temperatures (Table I, Fig. 1), a standard ORP with an output of 12 x 10^6 tons of refining oil per year was used as an example.

The Q-T diagram (Fig.1) shows that, out of all thermal power spent for oil refining (directly in processes) ~240 MW(t) is consumed at temperatures of up to 300 °C, ~500 MW(t) at temperatures of up to 430 °C, and ~125 MW(t) at the temperature range from 430 °C to 830 °C.

Table I Requirements for the ORP and the heat consumption

Parameter	Value
Total power consumption, MW(t), including:	1555
Power direct consumption for processing, MW(t)	865
Process steam generation, MW(t)	475
Electric power consumption, MW(t),	215
(with efficiency~ 30%), MW(e)	64.5
Main operating regime	Operation at the nominal power during at least 8000 hours per year Complete scheduled outage of production is not planned
Minimal power at reduction of load, % of nominal power	~25
Power change rate within the control range, %/ min.	1

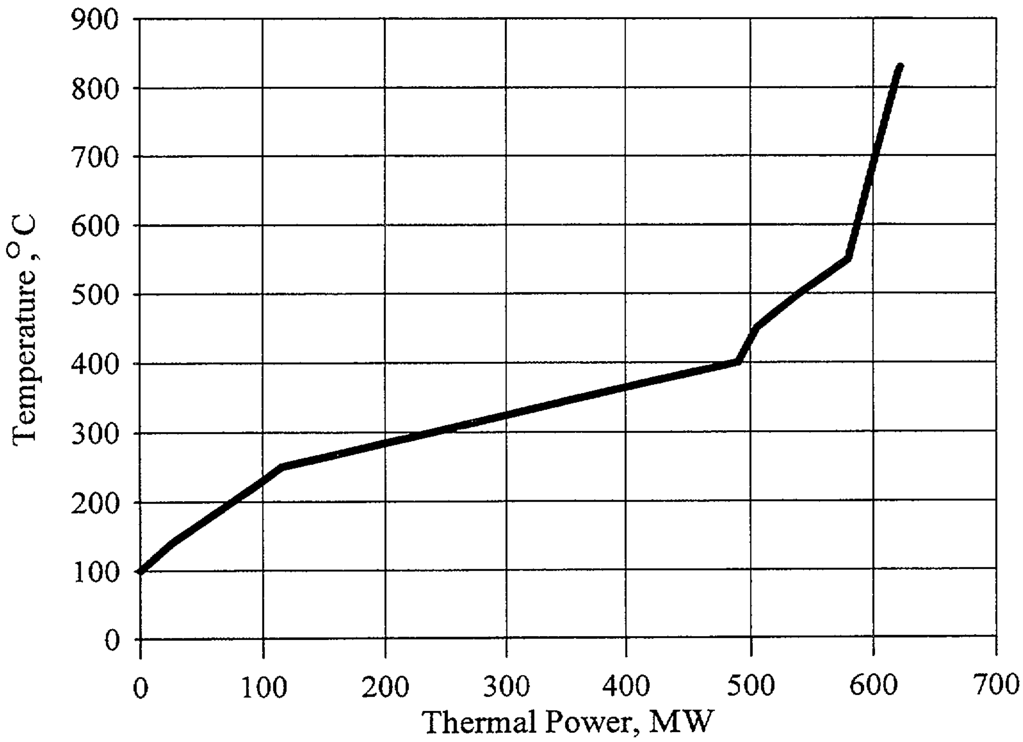


Fig. 1 Typical Oil Refinery Q-T Diagram

A modular HTGR with a pebble bed core that can be refuelled on power is selected as a nuclear heat source for the NPPS. The reactor of this type can provide a high level characteristics of heat supply: high load factor and high availability factor (up to 85 and 90 %, respectively). The reactor has a high level of safety due to inherent safety properties and passive principles if its power is limited to 200-250 MW [3].

The NPPS with such a reactor is possible to be located closer to the ORP and settlements. The power required for the processes can be obtained by an appropriate number of reactor units. Usage of multiple reactor units is better to meet requirements imposed by the oil refinery processes as noted below.

The first requirement is related to the power supply reliability during 8000 hours in consideration of refueling, planned and emergency shutdowns. No shutdowns are required for refueling of the modular reactor with a pebble bed core. At shutdowns and maintenance of one of the reactors, other reactors at the NPPS can supply minimum heat needed.

The second requirement is related to maneuverability over the all range of partial loads. At partial loads the operating temperature level can be maintained steady by shutdown of one or some selected reactor blocks, without changing the power level of other operatng units, than by changing the power level of a single block large NPP. This is possible when the required heat exchange area at partial loads in the intermediate circuit is less than the existing designed one, since multicircuit heat transfer lines connect the reactor and the consumer.

3. SYSTEMS OF HEAT REMOVAL

Capital investments and operating costs of NPPS depend essentially on the number and the length of heat exchange circuits. The number of heat exchange circuits is determined by the following requirements:

- to exclude the possibility of the final product contamination above the allowable levels according to codes and standards; and
- to exclude ingress of the intermediate coolants containing hydrogen or unremovable active and explosive substances to the primary circuit at the loss of integrity of heat exchangers.

Specific activity of a primary coolant in an HTGR is insignificant (~ 2 x 10^3 Bq/cm^3) and depends mainly on gaseous radionuclides (Xe^{133}, Xe^{135}, Kr^{88}). At an emergency outflow of helium from the primary circuit into the central hall of the reactor building the concentration of radionuclides in the ambient air will not exceed the requested level for working rooms. Long-term activity is determined by tritium (H^3) which is practically completely removed by the purification system. Anticipated tritium contamination of the intermediate circuit coolants will not exceed even the requested level for drinking water. Activation of the intermediate coolant by the neutron from the reactor could be reduced to the required values by design measures, such as, usage of step gas ducts limiting direct neutron flux; location of heat exchangers in a shielded concrete compartment.

The intermediate coolant ingress into the primary circuit at the loss of integrity of heat exchangers could be also excluded by design measures, for example, by decreasing the pressure of the intermediate coolant in comparison with the primary one and by releasing the intermediate coolant to the discharge tanks. Discharge tanks are located behind the protection membranes (rupture disks) beneath the gas ducts.

The length of heat exchange circuits is also determined by the following conditions:

- safety of the reactor plant;
- safety of the process (explosion, ejection of toxic substances, etc.); and
- disposition of heat consumers over a plant area.

As noted above according to the radioactivity safety requirements the NPPS with the VGM can be located not far from an ORP. The distance between the NPPS and the ORP will be determined by anticipated impacts on the NPPS by the accidents at the ORP. In addition, considering specific location of the consumer on the ORP area, the length of the heat transfer circuit to the consumer may be much longer than those of the primary and intermediate circuits.

4. HEAT TRANSFER MEDIA

The criteria of heat-transfer coolants selection were:

1) No phase transformation and thermal stability in the whole working temperature ranges including emergency modes;
2) High heat transfer coefficients (minimum heat exchanger areas);
3) Minimum power consumption for coolant circulation;
4) Reliability, simplicity and minimum costs for manufacturing and operation of the circuits; and
5) Safety in emergency modes.

The advantage of using the same coolants in circuits was also taken into account, since it reduces the number of auxiliary systems of heat transfer circuits. For the process circuits with temperatures of up to 550 °C, it is beneficial to utilize accumulated experience in oil refining and petrochemical plants.

With these considerations, following coolants were evaluated:

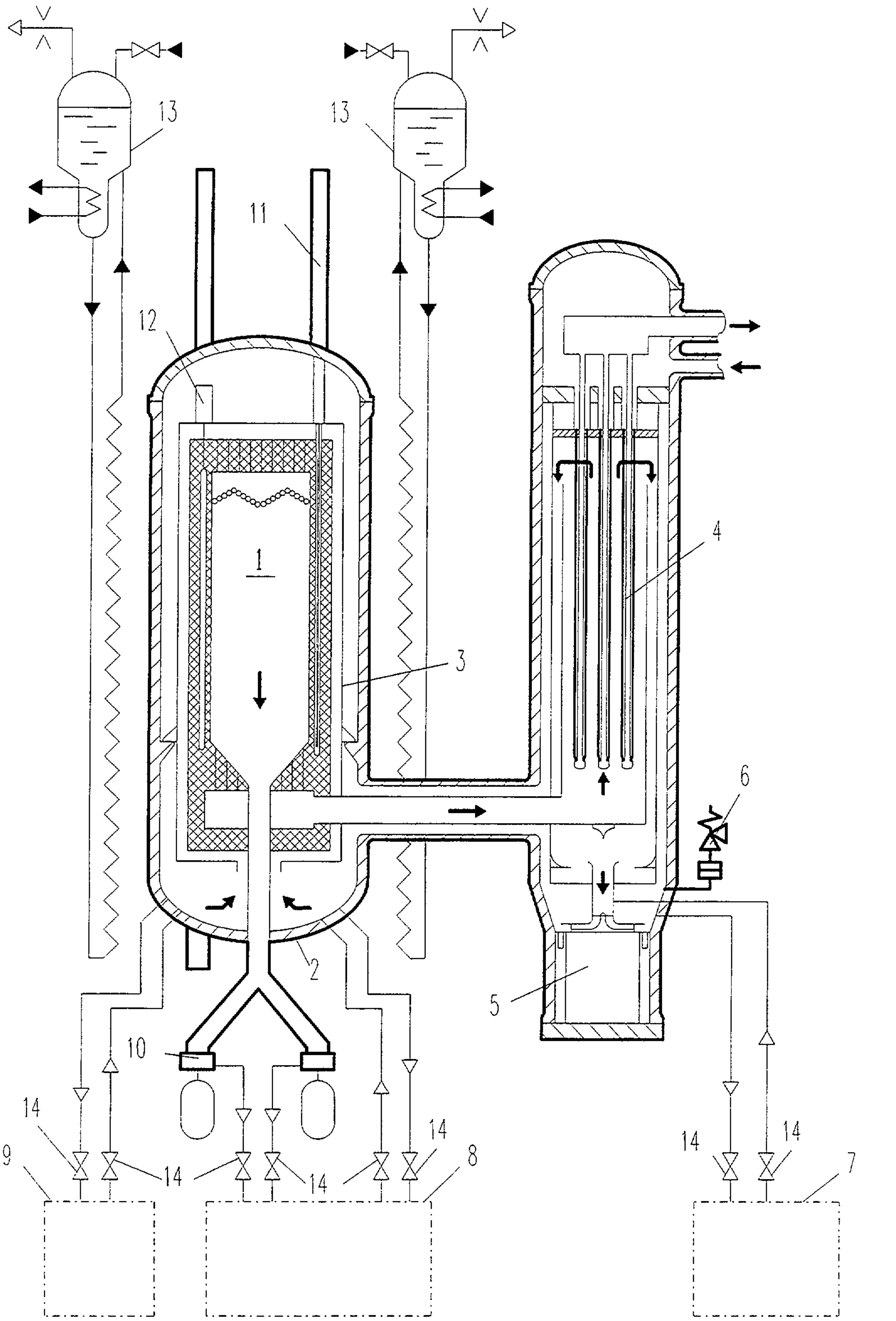
- helium, liquid metals (Na, Na-K, Pb-Bi) for the intermediate circuit with temperatures of up to 900°C;
- liquid metals (Na, Na-K) for the process circuit with temperatures from 550°C to 900°C;
- molten nitrate - nitrite salt on silicon oil for the process circuit with temperatures of up to 550°C.

A helium coolant used in the primary circuit of HTGRs, besides known advantages, has the disadvantages related mainly to the significant consumption of energy for circulation and the increased pressure and thickness of the pressure vessel and the gas ducts. Sodium and sodium-potassium coolants practically meet all requirements. However, they require complicated technologies for application, are rather expensive and have a fire potential at the coolant leak. In addition, the sodium coolant requires its pre-electric heating to its melting temperature (~ 97°C) before putting into service. The Pb-Bi alloy coolant is fire potential free, but has a number of essential shortages: significant consumption of energy for circulation, heavy weight, erosion and vibrating actions on structures, high cost, the necessity of pre-heating. The use of salt coolants in the intermediate circuit limits the temperature potential of transferring heat up to their work temperature of application ~550°C, although the temperature in HTGRs reaches 950°C.

The application of nitrate - nitrite salt as one of the most high temperature coolants has been proven by technological manufacturers [4]. However, its application is limited to the maximum temperature of 550°C, and above 450°C it begins to decompose resulting in the increased melting temperature and its replacement needed. It also requires pre-electric heating to the melting temperature of ~142°C. A silicon oil coolant has the best stability at the temperatures of 500°C -550°C and does not require pre-heating, as compared with salt coolants, as experienced in laboratory tests.

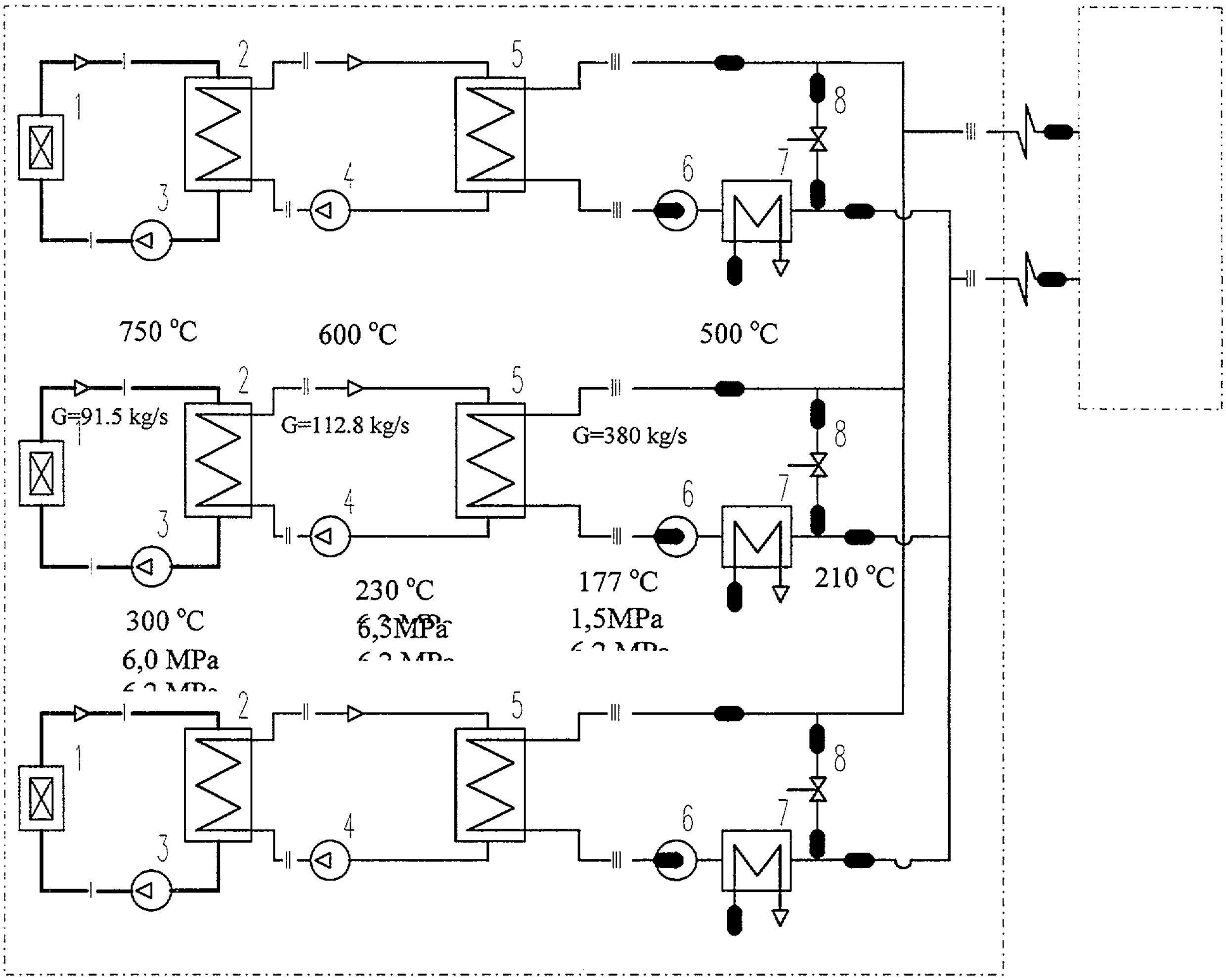
5. THE NUCLEAR POWER PROCESS STATION FOR A STANDARD OIL REFINERY PLANT WITH A MODULAR HTGR

In consideration of a significant fraction (~80 %) of heat need of up to 430 °C, and also in consideration of equipment developed for HTGRs and its readiness of manufacturing, a design of the NPPS for a standard ORP is carried out in OKBM based on the pilot industrial project of the VGM modular reactor. The NPPS consists of three VGM-P reactors of 215 MW power and the outlet helium temperature of 750 °C (Fig. 2). Three circuits for heat transfer to process furnaces (Fig.3) are adopted in the design. The number of the circuits are selected from a point of view of excluding a possibility of ingress of the process coolant into the reactor. Helium is recognized to be expedient as a coolant for the intermediate circuit and nitrate - nitrite salt coolant - for the process circuit. The intermediate circuits are designed to be independent for each reactor module to exclude common mode failures of the NPPS. The process circuit is common for all the ORP. It allows to ensure stable heat supply to the ORP in case of



1 - core; 2 - vessel system; 3 - leak tight core shell; 4 - intermediate heat exchanger;
5 - primary circuit circulator with cut-off valve; 6 - pressurization protection device;
7 - primary coolant purification system; 8 - refueling complex; 9 - small absorber balls system;
10 - fuel element unloading mechanism; 11 - control rod drive; 12 - small absorber balls system drive;
13 - emergency cooldown system; 14 - localizing valves.

Fig. 2 **VGM-P reactor sheet**



— I — Primary circuit
— II — intermediate circuit
— III — Third circuit

1 - reactor; 2 - intermediate heat exchanger; 3 - main gas blower; 4 - intermediate circuit gas blower; 5 - process heat exchanger; 6- technologic circulator; 7 - steam generator; 8 - bypass valve

Fig. 3 **NPPS flow scheme**

planned or emergency shutdowns of one of the reactors. The decrease of VGM-P outlet helium temperature down to 750 °C, in comparison with the base concept of VGM with the outlet helium temperature of 950 °C, allows to prolong the life time of the NPPS to not less than 40 years.

The condition for introducing HTGRs into the industry is its economic competitiveness in comparison with other energy sources. The major economic data of the NPPS with three VGM-P are presented in Table II. (The main economic indexes were taken in 1991 prices and at present are essentially different. Therefore the characteristics in the table should be considered as relative values).

Table II Major economic data of the NPPS with three VGM-P

Characteristic	Value
Thermal power transmitted to the consumer, MW(t)	500
Heat output, GJ/year	12,600 x10^3
Total investment, million rubles	1657.0
Operation expenses, million rubles/ year	209.1
Manufacturing cost of heat, rubles/GJ	16.6
Saving of natural gas, m^3/ year	340 x 10^3
Saving of oil, tons/ year	430 x 10^3

Calculations showed that, at the taken level of price of mazut (in 1991) of 2500 rubles per ton, the NPPS would reduce expenditures on fuel by more than 1 billion rubles annually.

Another effect of using NPPS for ORP would be the reduction of the adverse impacts on the inhabitants and the environment, which is caused by the pollution of the atmosphere resulting from the burning of the fossil fuel. This effect may amount to some dozens of millions of rubles per year.

6. CONCLUSION

The study of the NPPS project using three VGM-P industrial reactors of 215 MW power with the helium outlet temperature of 750°C showed that the plant can provide up to 80 % of heat consumption in the technological processes of a standard ORP. Mainly unavailability of acceptable process coolants restricts the residual 20 % of heat consumption of the high temperature level above 430°C.

The development of the industrial VGM-P with the helium outlet temperature of 950°C on the basis of the VGM project will make it possible to use scientific and engineering potential accumulated on VGM and its main components supported by research and development works.

The design experience of NPPS with VGM-P showed that one of the key points is a selection of a coolant for the intermediate and especially for the process circuits. Elimination of the intermediate circuit in VGM-P would reduce capital investments and operating expenses. This is the subject of further design developments.

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