PROPERTIES OF LEAD–BISMUTH COOLANT AND PERSPECTIVES OF NON-ELECTRIC APPLICATIONS OF LEAD–BISMUTH REACTOR

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Abstract

Key physical and chemical properties of lead-bismuth eutectic alloy are reviewed. Based on the low chemical activity of the alloy to other work media, a new concept of direct contact heat exchangers is proposed. A series of experiments were performed to validate the concept, using water, model salt solutions of sodium chloride, and oil. Key experimental results are summarized in the report.

PROPERTIES OF LEAD-BISMUTH COOLANT

The eutectic lead-bismuth (44,5%Pb, 55,5%Bi) alloy has a potential to used as a coolant in the primary circuits of special-purpose nuclear power installations. Table I shows some physical and thermal-physical properties characterizing this alloy from the viewpoint of its use as a coolant.

Table I Physical and Thermal-Physical Properties of Eutectic (44.5% weight Pb and 55.5% weight Bi) Lead/Bismuth Alloy

Melting temperature	- 396.6 K
Boiling temperature	- 1943 K
Volumetric expansion coefficient	- 1.19 x 10^{-4} K^{-1}
Volume change at melting	$-\Delta V = \frac{V_l - V_s}{V_s} \cdot 100 - (0 to 1.67)\%$

Dependence of some properties on temperature

Parameter	Temperature, °C					
	130	200	300	400	500	600
Density, ρ, kg/m^3	10570	10486	10364	10242	10120	10000
Heat capacity, c_p, J/kg·K	146	146	146	146	146	146
Kinematic viscosity, 10^8, m^3/s	31.4	24.3	18.7	15.7	13.6	12.4
Prandtl number, Pr·10^2	4.45	3.18	2.24	1.72	1.37	1.15
Heat conductivity, λ, W/m·deg.	10.93	11.74	12.67	13.72	14.65	15.81
Thermal conductivity, $a \cdot 10^6$, m^2/s	7.1	7.6	8.3	9.1	9.9	10.8

As compared with other liquid metals being used for the same purposes, its high density and the high boiling temperature are noteworthy. The latter property is the obvious advantage of this coolant, because it enhances the reliability and safety of the installations. Specific physical-chemical properties of lead-bismuth melts favour this too. Some properties of primary significance are presented in Table II.

Table II Physical-Chemical Properties of Pb-Bi Melt

Solution of some elements,
where C_s is the saturation concentration (mass %), and T is the temperature (K).

Oxygen: $\lg C_s = 1.2 - \frac{3400}{T}$ (T=673 to 973 K)

Hydrogen: $\lg C_s = -9.65 - \frac{670}{T} + 1.51 \lg P_{H_2}$ (T=398 to 773 K)

Iron: $\lg C_s = 2.01 - \frac{4380}{T}$ (T=823 to 1053 K)

Chromium: $\lg C_s = -0.02 - \frac{2280}{T}$ (T=673 to 1173 K)

Nickel: $\lg C_s = 1.53 - \frac{843}{T}$ (T=673 to 1173 K)

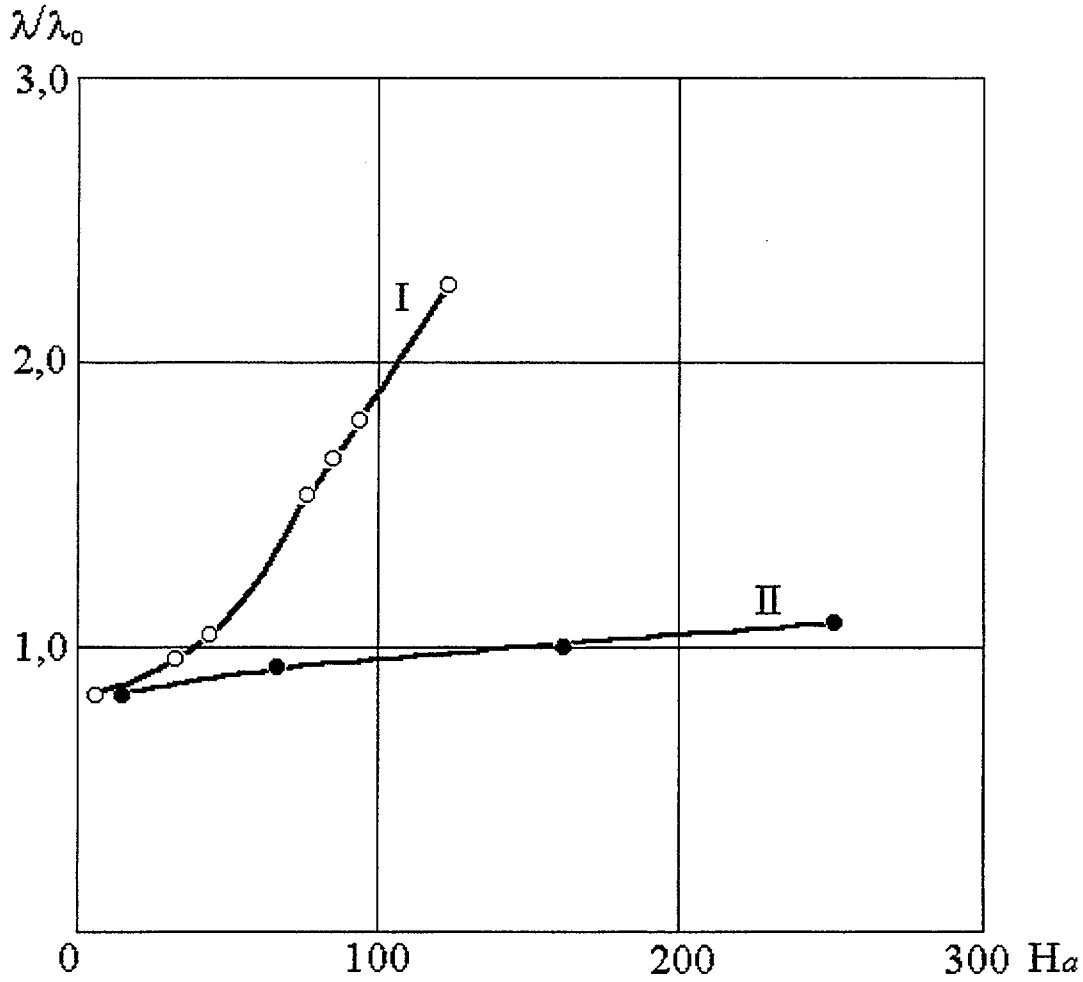
Interaction with some process impurities

Governing chemical reaction	Result of interaction
Water and steam	
$Pb+H_2O \leftrightarrow PbO+H_2$	Llead oxide slags are formed and the hydrogen is released. Accumulation is insignificant.
Air	
$Pb + \frac{1}{2} O_2 \leftrightarrow PbO$	Slags are formed. Amount of accumulation depends upon specific conditions of interaction. With the calm melt surface, the process is damped in time

It is worth noting that the chemical activity of the coolant to water, steam and air, i.e. to substances which can interact with the coolant in some accident conditions of the installation is relatively low. Among the causes of such inertia of lead-bismuth, the following two should be emphasized:

- the first cause is primarily related to the low chemical activity of melt components, ranging in the region close to the noble metals;
- the second cause is related to the ability of this alloy to form on the interface with interacting substance thin layers from the products of this interaction, which prevent further proceeding of the process. In the case of oxidation by air, these layers consist of melt components oxides and in the case of interaction with structural steels of oxides - of components of these steels.

The experimental data on a substantial reduction of hydraulic resistance when the melt flows in the strong magnetic fields illustrate the effect of such layers on coolant properties. Experimental results are presented in Fig.1 in the form of the relative resistance coefficient versus the Ha number, which is proportional to the magnetic field strength. As evident from the figure, the effect of the presence of oxidic layer on the tube surface is remarkable, and it becomes more substantial, as the strength of the magnetic field increases. Thus, unlike other liquid metals, this Pb-Bi coolant is suitable for heat removal in the strong magnetic fields.



$$\lambda_0 = 0{,}0032 + \frac{0{,}221}{Re^{0{,}237}}$$

$$H\acute{a} = \acute{a} B_0 (\sigma/\eta)^{0{,}5}$$

$$Re = 2{,}2x10^5$$

$$T = 300\ ^0C$$

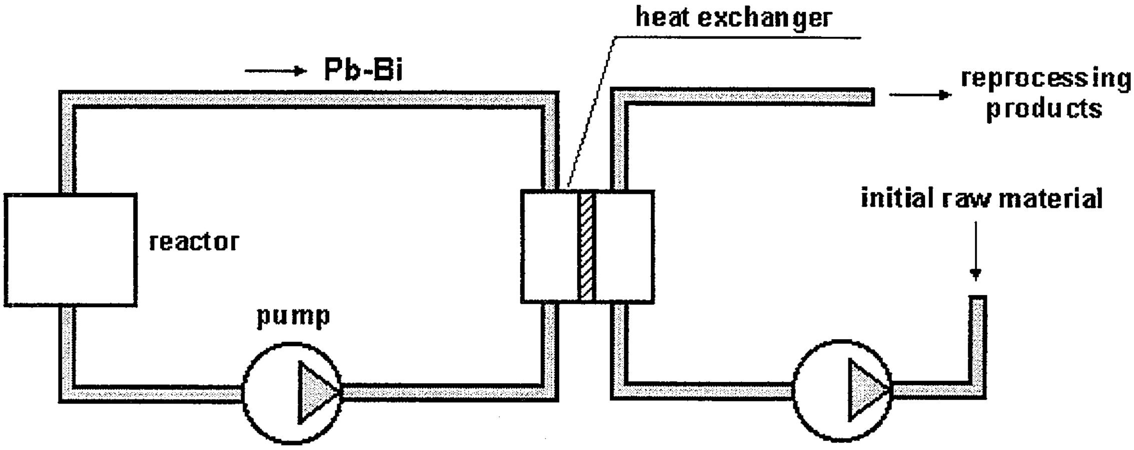
Comparison of Resistance Coefficients for Non-Oxidized (I) and Oxidized (II) Tubes with Pb-Bi Alloy Flow in Cross Sectional Magnetic Field.

FIG. 1. POSSIBILITIES OF USING LEAD-BISMUTH COOLANT FOR HEAT REMOVAL IN STRONG MAGNETIC FIELDS

It should be emphasized that the study of lead-bismuth melt properties and processes carried out on the closed circulation loops made it possible to develop both theoretically and practically a technology and rules for handling this coolant, enabling all questions related to its use in the nuclear power installations to be positively settled.

Regarding the non-electroenergetic use of facilities with the lead-bismuth coolant, Fig.2 shows two absolutely different diagrams, in particular, for the technological processes which require the large amounts of heat supply, for instance, in desalination, oil refining and in some other chemical processes. In the upper part of the figure, a conventional circuit of heat transmission is presented, where heat transfer is implemented in the standard heat exchangers with a partition baffle between the primary coolant and the medium to be reprocessed.

Traditional reprocessing circuit



Non-traditional reprocessing circuit with using direct-contact heat exchangers

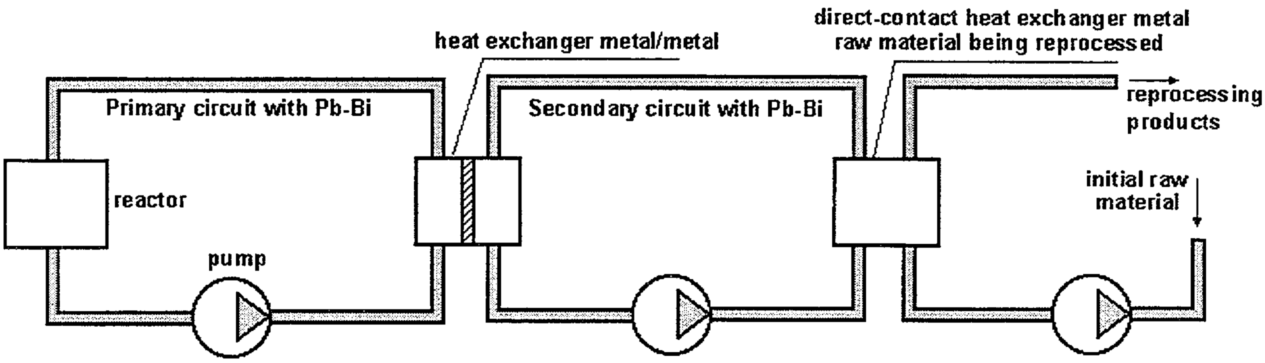


FIG. 2 FLOW DIAGRAM OF POTENTIAL USING OF NUCLEAR POWER INSTALLATION WITH LEAD-BISMUTH COOLANT FOR REPROCESSING VARIOUS ORGANIC AND NON-ORGANIC LIQUID AND GASEOUS MEDIA

The use of lead-bismuth reactor in such a circuit does not pose any additional problems. In principl, it is necessary to solve the problem by manufacturing a reliable tube-in-shell heat exchanger which has no significant problem of corrosion and slagging induced by the coolant and raw materials.

The lower part of the figure shows a new concept of the reprocessing circuit with direct-contact heat exchangers. It has a three-loop scheme where a heat exchanger for direct mixing of raw materials with the secondary circuit coolant is present. The use of such a heat exchanger can be shown to be beneficial in a number of cases. The advantages and disadvantages of such heat exchangers are well known and are summarized below.

Main Advantages and Disadvantages of Direct-Contact Heat Exchangers

Advantages:

- low hydraulic resistances;
- potentially higher specific loadings;
- ability of transferring heat at more lower temperature differences;
- simple design;
- lower cost;
- **free of problems of heat transfer surface corrosion and slagging.**

Disadvantages:

- necessity of maintaining similar pressures at places of mixing;
- **possible mutual contamination of contacting media.**

However, it should be noted that such positive factors as the absence of corrosion and slagging on the heat exchange surface is leveled to some extent by the problem of mutual contamination of contacting media.

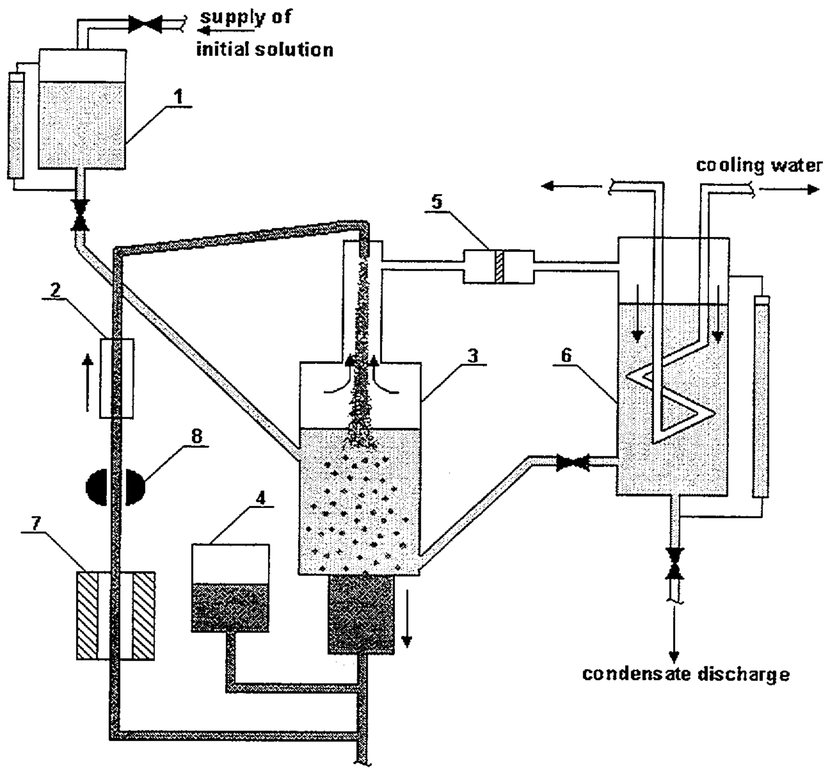
As it was shown above, the properties of the lead-bismuth coolant give good prospects that it will be sufficiently inert not only to water and steam but also to quite a number of other substances including organic ones. To validate this, mock-ups of direct-contact heat exchangers and test facilities were fixed. Some of them are demonstrated in Figs.5[1] and 6. The test facilities simulated different versions of the melt contact with other liquid media under the conditions of both forced and natural circulation of the melt to be investigated. A large number of tests were conducted, where distillate or process water, model salt solutions of sodium chloride with the initial sodium concentration of ~3% to ~30% mass, as well as oil were used as a raw material for reprocessing. The duration of experimental investigations varied on different test facilities from several hours to several hundreds of hours. The results of conducted investigations are shown in Table III, and they can be summerized as follows:

Table III **Main Results of Conducted Experimental Investigations**

Type of reproces-sed raw material	Duration of mock-up operation in an experiment, τ, h	Melting temperat ure, T, ^{O}C	Availability of reprocessing product purification system	Level of melt contamination by impurities, C, % weight	Level of reprocessing liquid product contamination, C, mg/l
Water	τ=20 to 600	500 to 350	not available	C_{O2} ~$2x10^{-6}$	C_{Pb}~0.2 C_{Bi}~0.6
	τ=2 to 10	400÷350	available	C_{O2} ~$2x10^{-6}$	C_{Pb}~0.02 C_{Bi}~0.003
Model salt solutions of sodium chloride, C_{NaCl}=3 to 30 % mass	τ=2 to 10	400 to 300	not available	C_{O2} ~$2x10^{-6}$	C_{pb}~10 to 1 C_{bi}~4 to 0.2
	τ=2 to 10	400 to 300	available	C_{O2} ~$2x10^{-6}$	C_{pb}~0.7 to 0.6 C_{bi}~0.8 to 0.1
Oil	τ=100 to 140	500 to 300	not available	Volumetric contamination is not detected	Light fractions C_{pb}~0.08 to 0.05 C_{bi}~0.02 to 0.01 Heavy fractions C_{pb}~4 to 0. 1 C_{bi}~0.2 to 0.05

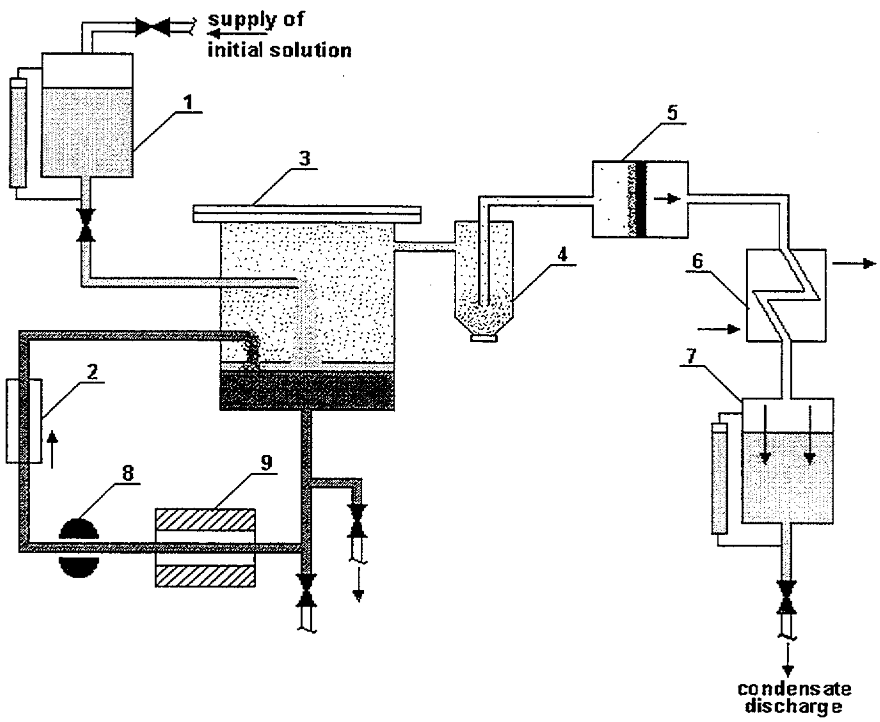
While the lead-bismuth coolant is interacting with the above listed liquid media within a temperature range of ~500^{O}C to 300^{O}C, the coolant contamination by the components of the raw material being reprocessed was not detected during the tests and after their termination, except the oxygen impurity (when interacting with water and water solution). At the same time it was confirmed that the

[1] Because of editing reasons, there are no Fig. 3 and 4.



1. flow rate tank
2. primary heater
3. contact apparatus
4. buffer reservoir
5. filter
6. condenser
7. electromagnetic pump
8. flowmeter

a) Closed-circuit or open-circuit relative to raw material reprocessing



1. flow rate tank
2. primary heater
3. contact apparatus
4. cyclone
5. filter
6. cooler
7. accumulation reservoir
8. flowmeter
9. electromagnetic pump

b) Open-circuit relative to raw material reprocessing

Fig. 5. Schematic Diagram of Direct-Contact Device Mock-Up with Forced Circulation of Coolant

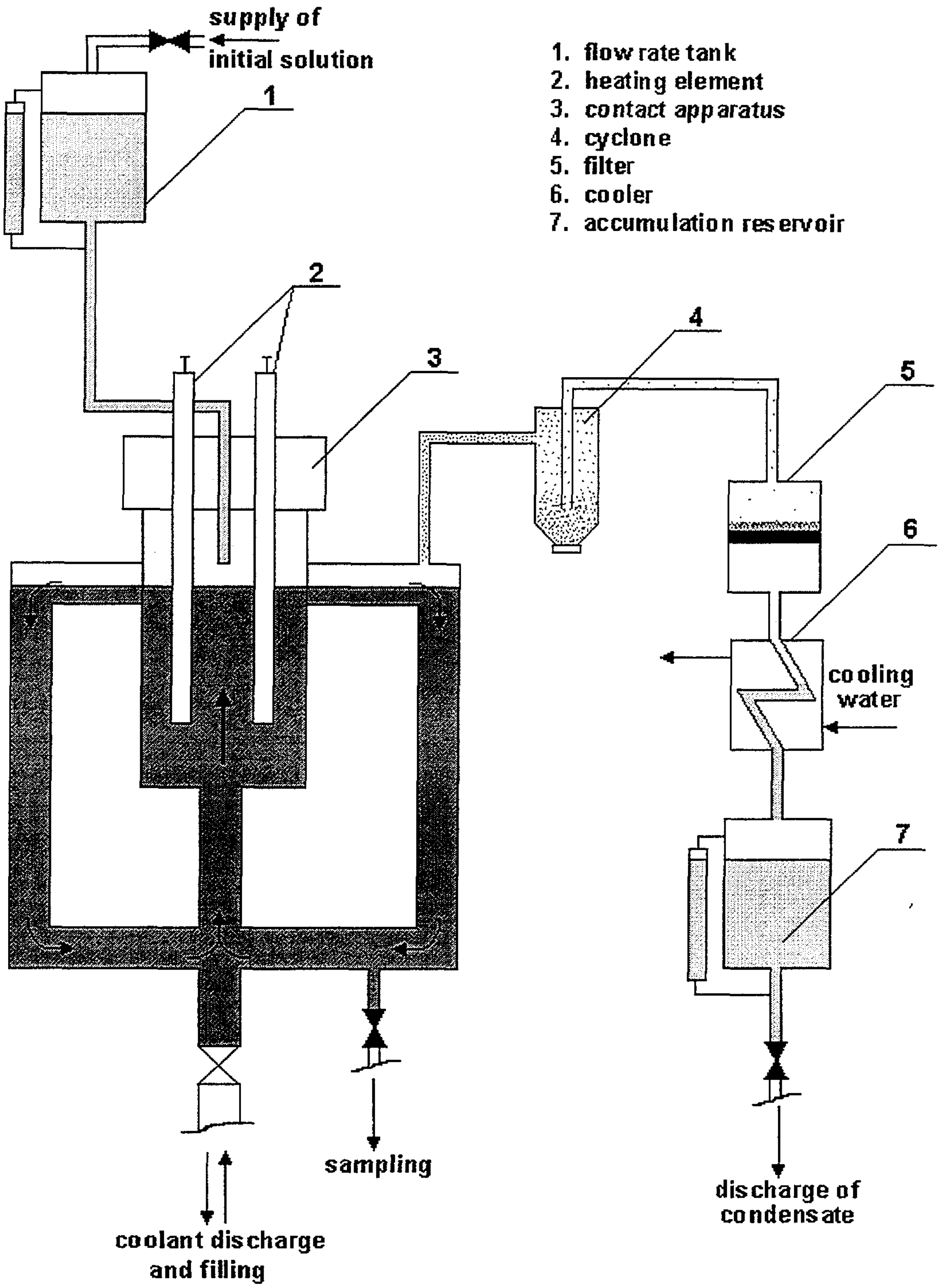


Fig. 6. Schematic Diagram of Direct-Contact Device Mock-Up with Free Circulation of Coolant

initial coolant is purified from electronegative impurities (Fe, Cr, etc.) in a number of cases due to the oxidative refining of the melt in the course of its interaction with water and steam.

With the time, the concentration of the melt components in the liquid raw material reprocessed products was observed to increase. The concentration of lead, a more chemically active substance, was higher than that of bismuth. This difference reached sometimes an order of magnitude and even bigger.

The products contamination rate was evaluated in terms of one year of continuos operation of the facility depending on the type of raw material being reprocessed and the conditions of the direct contact.

Simplest devices such as cyclones, inertial precipitator and metal-ceramic filters for the purification of reprocessed products from impurities, turned out to produce much purer condensed products.

The tests as performed have shown that the problem of the mutual contamination of the coolant and the contacting raw materials tested for reprocessing can be perfectly solved by the existing methods and devices for the liquid and gas purification. The mixer-type heat exchangers with a lead-bismuth alloy can be competitive with conventional tube-in-shell heat exchangers in some cases and can be used in non-electroenergetic technologies for a lead-bismuth coolant.