

# Cavitation Separation of Nano- and Microscale Monomineral Fractions from Polyminerale Microparticles

V. V. Adushkin<sup>a</sup>, S. N. Andreev<sup>b</sup>, and S. I. Popel<sup>a</sup>

<sup>a</sup>*Institute of Geosphere Dynamics, Russian Academy of Sciences, Leninskii pr. 38-1, Moscow, 119334 Russia*

<sup>b</sup>*Prokhorov General Physics Institute, Russian Academy of Sciences, ul. Vavilova 38, Moscow, 119991, Russia*

Received February 15, 2007

**Abstract**—Possible cavitation disintegration of polyminerale microparticles placed into a liquid as a result of interaction of particles with collapsed cavitation bubbles is shown for the minerals most abundant in gold ore. The bubbles are generated by shock loading of the liquid heated to the boiling temperature. The possibility of cavitation separation of nano- and microscale monomineral fractions from polyminerale microparticles is demonstrated.

**DOI:** 10.1134/S1075701507030038

## INTRODUCTION

The exhaustion of high-grade deposits in the process of mining and production of noble metals demands enhancement of the efficiency of development of low-grade deposits and reprocessing of ore dumps and tailings, which contain a certain amount of noble metals in the form of finely disseminated fractions. The recovery of disseminated metals from fractions no more than 100  $\mu\text{m}$  in size is a complicated problem (Nekrasov, 1988). In this paper, we consider the possibility of fragmentation of microscale polyminerale ore particles into monomineral fractions on the basis of cavitation melting of mineral micro- and nanoparticles in liquids (Adushkin et al., 2004a, 2004b, 2006; Novgorodova et al., 2003a, 2003b).

The proposed method is the following. Ore microparticles that contain finely disseminated fractions of noble metals are placed into a cavitation chamber filled with a liquid (water) heated up to the boiling temperature. It is known that, in the process of heterogeneous boiling, the bubbles in a liquid nucleate and grow mostly on foreign inclusions: dust particles, roughnesses of the vessel walls, etc.; therefore, ore microparticles will serve as natural centers of cavitation bubble nucleation. If the pressure in the cavitation chamber rises abruptly, for instance, owing to shock loading by a plunger (press), the cavitation bubbles will collapse. Compression and collapse of a cavitation bubble is commonly accompanied by an abrupt local rise in temperature and pressure that can induce melting of an ore microparticle attached to the bubble and lead to its subsequent separation into monomineral fractions. The monomineral fractions obtained by cavitation melting may afterward be divided using standard techniques, e.g., gravity or chemical separation.

The mechanism of cavitation melting was discussed by Novgorodova et al. (2003a) in explaining the origin of microscopic globules found in cavities and fractures of vein quartz from mesothermal gold deposits (Gamyagin et al., 1999). Using a simplified model that did not take into account specific values of the cavitation bubble radius, Novgorodova et al. (2003a) showed that interaction between a collapsed cavitation bubble and refractory particles of micrometer dimensions (quartz, gold) in a hydrothermal fluid may cause their melting if the maximum radius of the bubble equals  $\sim 1$  cm. Adushkin et al. (2004a, 2004b, 2006) developed an internally consistent theory that describes the cavitation mechanism of mineral nano- and microspherule formation in hydrothermal fluids taking into account typical dimensions of cavitation bubbles and their evolution along with the dynamics of particle heating in cavitation bubbles. On the basis of this theory, the maximum dimensions of cavitation bubbles were estimated, as well as the size of globules generated due to the melting of particles of different mineral composition under cavitation effects in hydrothermal fluids. It was shown that the cavitation mechanism may bring about the formation of mineral and metallic nanospherules in hydrothermal fluids. The formation of nano- and microspherules with regard to the depth of host rock was also investigated.

In this paper, we provide insights into the separation of polyminerale microparticles into monomineral fractions in the process of interaction of polyminerale microparticles with collapsed cavitation bubbles and propose a conceptual design of a device for separation of microparticles.

## CAVITATION MELTING OF MINERAL MICROPARTICLES IN GOLD ORE

The mineral and chemical compositions of ores at large gold deposits, such as Cripple Creek (United

Physical parameters of the minerals from gold ore

| Mineral  | Formula                        | $\rho$ , g/cm <sup>3</sup> | $\chi$ , cm <sup>2</sup> /s | $T_m$ , K |
|----------|--------------------------------|----------------------------|-----------------------------|-----------|
| Gold     | Au                             | 19.3                       | 1.3                         | 1336      |
| Silver   | Ag                             | 10.5                       | 1.73                        | 1235      |
| Quartz   | SiO <sub>2</sub>               | 2.14                       | 0.042                       | 1883      |
| Pyrite   | FeS <sub>2</sub>               | 4.9                        | 0.15                        | 1461      |
| Galena   | PbS                            | 7.3                        | 0.23                        | 1387      |
| Calcite  | Ca(CO <sub>3</sub> )           | 2.71                       | 0.017                       | 1885      |
| Stibnite | Sb <sub>2</sub> S <sub>3</sub> | 4.6                        | 0.145                       | 819       |

States), Bagio (Philippines), and Pueblo Viejo (Dominican Republic), and at gold deposits in Russia are fairly complex (Nekrasov, 1988; Foss, 1963), although the number of major minerals is relatively few. Native gold often occurs together with quartz and is always associated with iron, copper, antimony, lead, and zinc sulfides. Quartz, barite, and carbonates are the major gangue minerals. In addition to native gold, the primary ores contain pyrite, arsenopyrite, sphalerite, and galena.

Several of the most abundant and important minerals of gold ore were chosen for the numerical analysis of the cavitation melting effect. Their physical parameters (density  $\rho$ , thermal diffusivity  $\chi$ , and melting temperature  $T_m$ ) necessary for calculations are given in the table.

The dynamics of cavitation bubble compression in response to an abrupt rise of pressure  $P_0$  in the cavitation chamber due to shock loading was calculated with a numerical method using a model developed by Adushkin et al. (2004a, 2004b). As is assumed by the model, water heated up to the boiling temperature  $T_0 = 373$  K is an incompressible liquid with a density of  $\rho = 1$  g/cm<sup>3</sup>; the state of the vapor in the bubble is described by the van der Waals equation with the critical parameters  $T_c = 647$  K and  $P_c = 225$  bar. The dynamics of the bubble compression in this case is described by the Rayleigh–Plesset equation (Margulis, 2000):

$$R\ddot{R} + \frac{3}{2}\dot{R}^2 = \frac{1}{\rho} \left\{ (P(R) - P_0) - \frac{4\eta\dot{R}}{R} - \frac{2\sigma}{R} \right\}, \quad (1)$$

where  $R(t)$  is the radius of the bubble;  $\dot{R}$  and  $\ddot{R}$  are the first and second time ( $t$ ) derivatives of the bubble radius; and  $\eta$  and  $\sigma$  are the viscosity and surface tension of the liquid, respectively. The pressure  $P(R)$  inside the bubble as a function of its radius  $R$  is determined from the equation of the adiabatic process for a nonideal gas with the adiabatic exponent  $\gamma = 4/3$ .

A spherical symmetry of the heat conduction problem was suggested to simplify calculations of heating and melting dynamics of a solid microparticle interacting with a collapsed cavitation bubble: a spherical microparticle is located in the center of the contracting bubble; the thermal effect of the particle on the bubble may be ignored. The time-dependent temperature dis-

tribution within the microparticle  $T_p(r, t)$  is described by a thermal conduction equation in which the variation of temperature due to microparticle melting may be neglected. The initial temperature within the microparticle is assumed to be constant and equal to the temperature in the surrounding bubble. The temperature on the microparticle surface is controlled by the variable temperature of the surrounding vapor. The condition of symmetry is set at the microparticle center.

A solid microparticle within a collapsed bubble or at its surface starts to melt when the entire microparticle is heated up to a temperature that exceeds the melting temperature  $T_m$  of the microparticle substance, which is 1350 K for gold and 1883 K for quartz. The maximum radius  $R_{p, \max}$  of a microparticle that is completely converted into melt during the bubble collapse is controlled by the microparticle composition, the initial radius  $r_0$  of the bubble, and the pressure  $P_0$  and temperature  $T_0$  of the liquid. The relationship of  $R_{p, \max}$  of mineral microparticles listed in the table versus  $r_0$  at  $T_0 = 373$  K and  $P_0 = 15$  bar is shown in Fig. 1. The temperature  $T_0 = 373$  K ensures that bubbles naturally arise in the boiling water, and the selected  $P_0 = 15$  bar maintains the temperature within the bubble at the moment of its maximum compression above the melting temperature of all the considered minerals. The dashed line indicates the 1- $\mu$ m level, below which particles fall within the nano-sized range, where the size varies from 1 to 1000 nm. The straight graphs  $R_{p, \max}(r_0)$  in the double logarithm scale indicate the exponential character of these relationships.

The slope of the straight lines in Fig. 1 does not depend on the material of microparticles; therefore, the exponent  $\alpha$  in the  $R_{p, \max}(r_0)$  value is the same for all minerals. The calculations show that  $\alpha = 1/2$ . Thus, the maximum radius of a microparticle completely melted in the process of bubble collapse depends on  $r_0$  according to the following universal law:

$$R_{p, \max}(r_0) = R_{p1} \sqrt{r_0}, \quad (2)$$

where the factor  $R_{p1}$  is determined by the microparticle material and the pressure  $P_0$  in the liquid. Metals and ore minerals are characterized by the highest  $R_{p1}$  values, whereas nonmetallic minerals with a low thermal diffusivity and high melting temperature have the lowest  $R_{p1}$ . Hence, if  $r_0 = 1$  cm,  $T_0 = 373$  K, and  $P_0 = 15$  bar, then  $R_{p, \max} = 135$   $\mu$ m for gold and 14  $\mu$ m for quartz.

The relationship between the coefficient  $R_{p1}$  in (2) and  $P_0$  of the liquid surrounding the bubble at  $T_0 = 373$  K is shown in Fig. 2 for various minerals. As can be seen from Fig. 2, the relationships  $R_{p1}(P_0)$  are not monotonic and have a threshold character: when  $P_0$  increases above the threshold  $P_{0t}$  value, the  $R_{p1}$  value first increases, reaches a maximum, and then decreases. Different minerals are characterized by specific  $P_{0t}$  threshold values and positions of  $P_{0\max}$ ; for instance, for

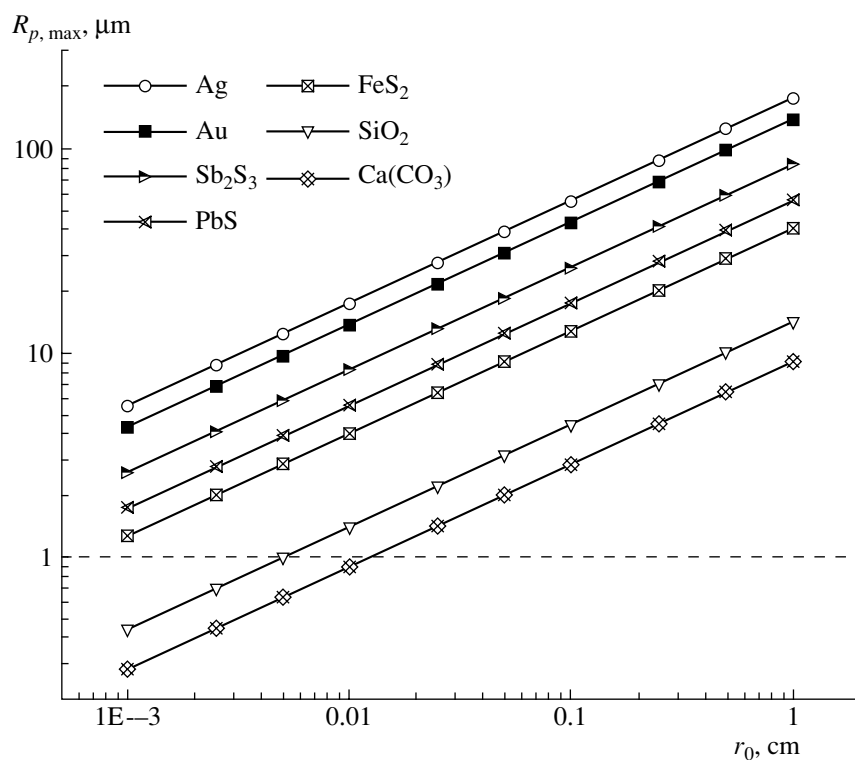


**Fig. 1.** Relationship between the maximum radii  $R_{p, \max}$  of microparticles melted during the cavitation bubble collapse and its initial radius  $r_0$  at  $T_0 = 373$  K and  $P_0 = 15$  bar.

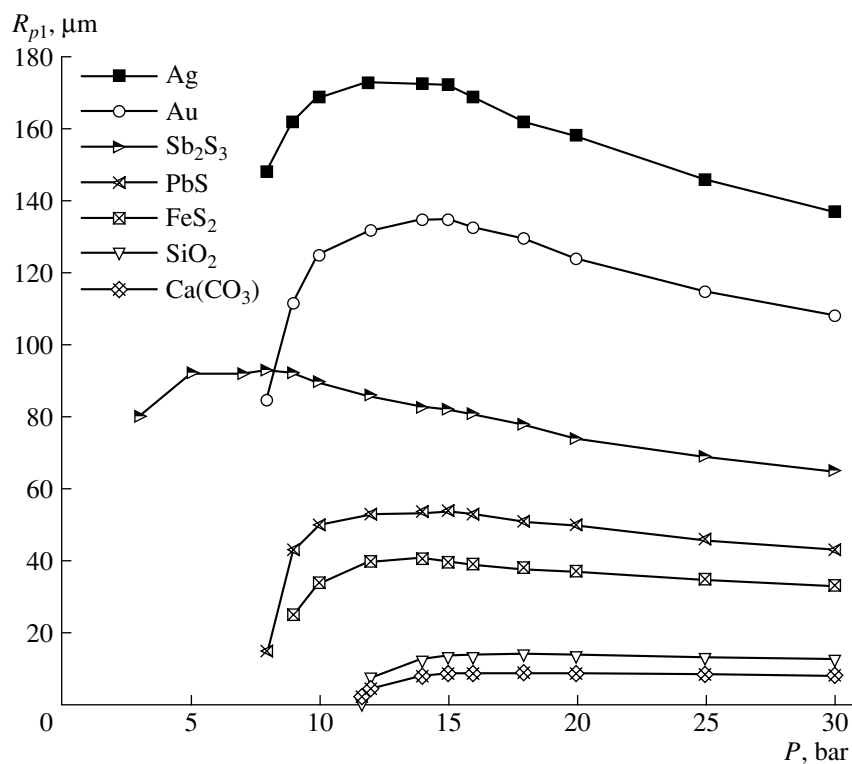


**Fig. 2.** The coefficient  $R_{p1}$  versus the pressure  $P_0$  in the liquid at  $T_0 = 373$  K.

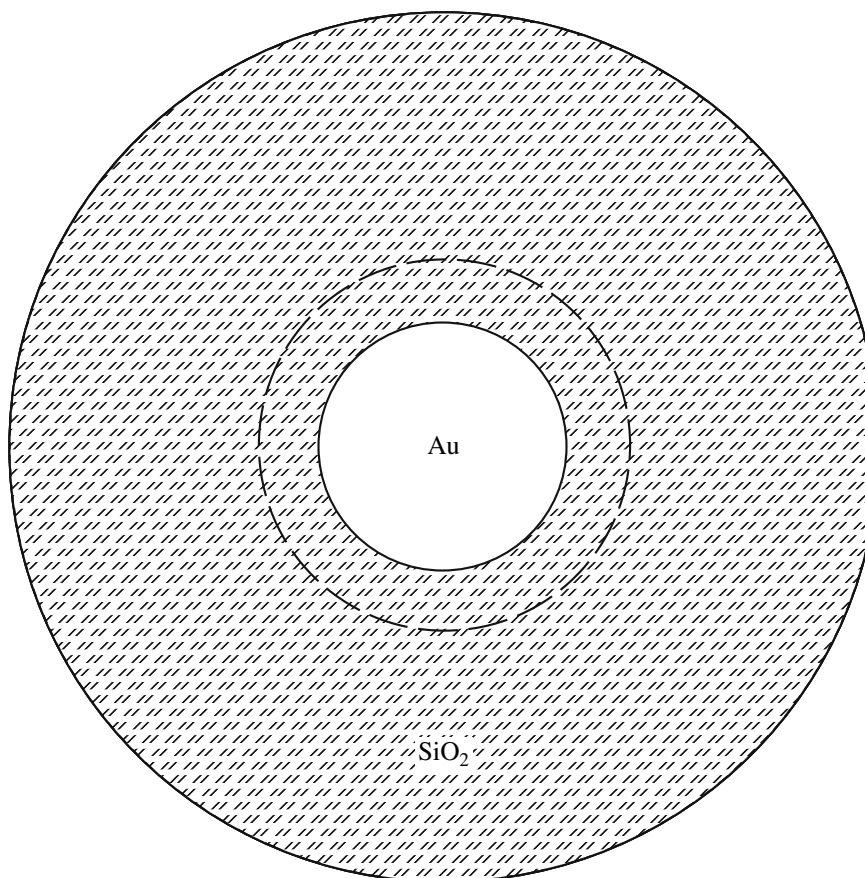


**Fig. 3.** Schematic image of native gold incorporated into a quartz microparticle. The dashed line shows the expansion of the gold particle during melting.

gold,  $P_{0r} = 8$  bar and  $P_{0max} = 15$  bar; for stibnite,  $P_{0r} = 3$  bar and  $P_{0max} = 8$  bar; and for quartz,  $P_{0r} = 11.7$  bar and  $P_{0max} = 18$  bar.

The shape of the curves in Fig. 2 is explained by the fact that an increase in the pressure of the liquid leads to the rise of the maximum temperature in the cavitation bubble at the moment of its highest compression, on the one hand, and shortens the duration of the collapse stage, that is, the time during which a high temperature is maintained in the bubble, on the other hand. Therefore, the threshold value of the  $P_{0r}$  pressure is determined by the condition of reaching the melting temperature of the mineral microparticle in the bubble. If  $P_0$  becomes higher than  $P_{0max}$ , the coefficient  $R_{p1}$  starts decreasing because the reduced duration of the collapse stage turns out to be more significant than the temperature rise in the bubble.

The cavitation melting of monomineral microparticles has been considered above. Let us turn to a case where a quartz particle contains a finely disseminated gold inclusion (Fig. 3). Figure 4 displays the relationship between  $R_{Au, max}$  of a melted spherical gold microparticle located in the center of a spherical quartz grain and its radius  $R_{SiO_2}$  in the process of interaction with a

bubble at  $r_0 = 1$  cm; the temperature and pressure of the surrounding water are equal to  $T_0 = 373$  K and  $P_0 = 15$  bar, respectively. If  $R_{SiO_2}$  increases within the range  $24 \leq R_{SiO_2} < 30$   $\mu\text{m}$  (Fig. 4), the maximum size of the gold microparticle diminishes from  $R_{Au, max} \approx R_{SiO_2} = 24$   $\mu\text{m}$  to  $R_{Au, max} = 5$   $\mu\text{m}$  at  $R_{SiO_2} = 29.5$   $\mu\text{m}$ . At  $R_{SiO_2} < 24$   $\mu\text{m}$ , a gold microparticle of any size not exceeding  $R_{SiO_2}$  turns out to be melted because, in that case, the temperature of the quartz grain, even if it does not contain gold disseminations, is above the melting temperature of gold (1336 K) while the bubble collapses.

It is known that, in the process of melting, the density of gold decreases from  $\rho_s = 19.3$  g/cm<sup>3</sup> to  $\rho_l = 17.31$  g/cm<sup>3</sup>; i.e., the volume of the gold particle changes by  $\rho_s/\rho_l = 1.12$  times. If the melted particle is incorporated into quartz and its expansion is impossible, it will be compressed by  $\rho_s/\rho_l = 1.12$  times, with a corresponding increase in pressure. The pressure that arises during the melting of a gold particle incorporated into quartz may be estimated using the coefficient of

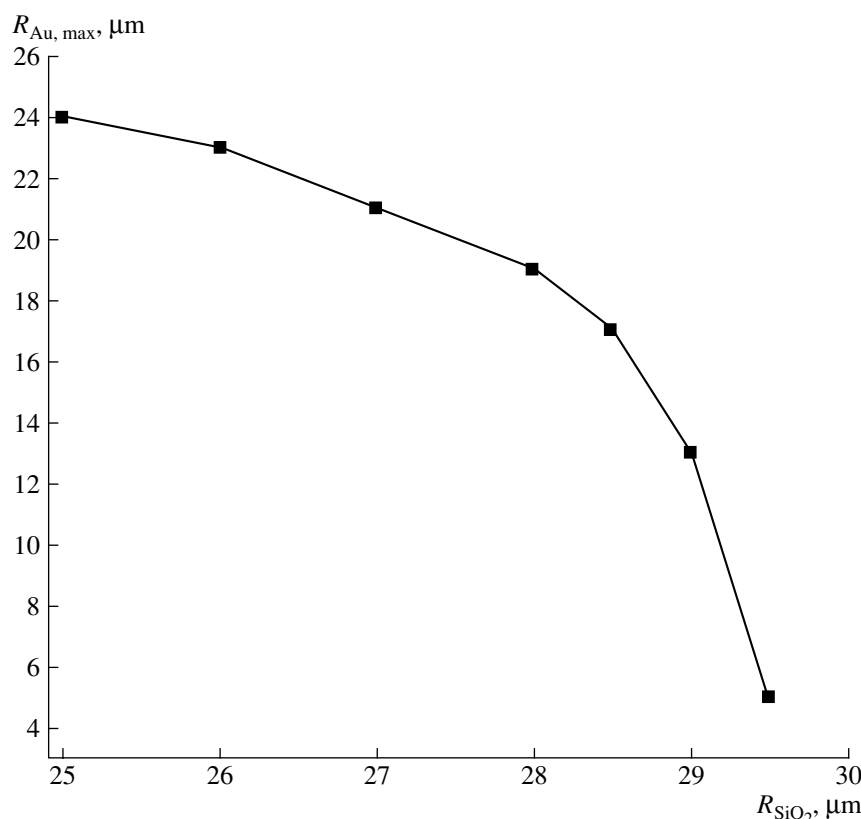


**Fig. 4.** Relationship between the maximum radius  $R_{Au, max}$  of a melted spherical gold microparticle located in the center of a spherical quartz grain and its radius  $R_{SiO_2}$  at  $r_0 = 1$  cm,  $T_0 = 373$  K, and  $P_0 = 15$  bar.

volumetric expansion of gold  $K = 2.2$  Mbar from the formula

$$P_m = K \left( 1 - \frac{\rho_l}{\rho_s} \right) = 0.24 \text{ Mbar.} \quad (3)$$

Such a high pressure, several times higher than the strength of quartz (90 kbar), results in the breakup of quartz and separation of the polymineral particle into monomineral fractions.

Thus, the calculations performed above show that the effect of the cavitation melting of microparticles composed of minerals characteristic of gold deposits can be realized under shock loading of water heated up to the boiling temperature at  $P_0 \approx 15$  bar. As a result of the cavitation melting, the interaction of polymineral microparticles with collapsed cavitation bubbles may lead to breakup and fragmentation of microparticles into monomineral fractions.

#### CAVITATION DEVICE DESIGN

The possibility of cavitation melting of microparticles, both micro- and nanosized, incorporated into polymineral fractions allows us to propose a method of cavitation separation of such particles. The detailed

development of the method is a subject of future investigations. A conceptual design of a device for separation (breakup into monomineral fractions) of polymineral microparticles from gold ore is shown in Fig. 5.

A cavitation chamber is filled up with a liquid (water, for example) that contains ore microparticles and is heated with a thermostat to the boiling temperature (373 K for water). Nuclei of vapor bubbles arising on ore microparticles will grow until the ambient pressure exceeds 1 bar. Shock loading with a plunger ensures an abrupt rise in pressure in the chamber to 10–15 bar, initiating collapse of the bubbles attached to microparticles and fragmentation of polymineral particles into monomineral fractions. To enhance the efficiency of fragmentation, the shock loading may be applied periodically. After removal and filtering out of monomineral fractions from the cavitation chamber, the heated water can be used for cavitation separation again.

To optimize the work of the cavitation chamber with ores derived from particular gold deposits, the following parameters should be taken into consideration.

1. *Mineral composition of ore.* A preliminary analysis of the mineral composition of ore is necessary in order to choose an optimal working pressure  $P_0$  in the chamber. As was shown, 15 bar is an optimal pressure for the cavitation melting of gold. Because the  $R_{p1}(P_0)$

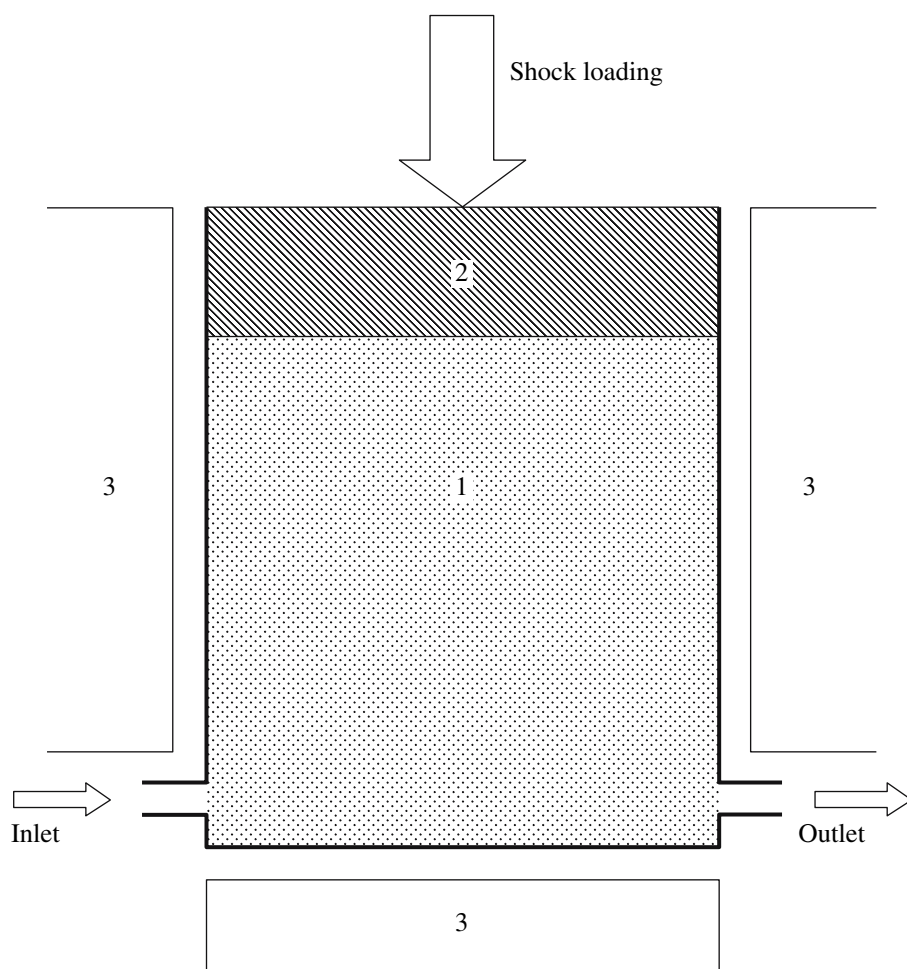


**Fig. 5.** A conceptual design of a device for cavitation separation of gold-bearing particles. (1) Cavitation chamber with liquid (water) containing ore microparticles; (2) plunger providing shock loading (an abrupt rise in pressure in the chamber to 10–15 bar); (3) thermostat maintaining a temperature  $T_0 = 373$  K in the cavitation chamber.

relationship is of threshold nature, if necessary, the regime of the chamber's work may be chosen in such a way that microparticles of one sort will melt, while others remain in the solid state.

**2. Distribution of microparticles by size.** Depending on the mode of mining and grinding of gold ore, the distribution of mineral microparticles by size may be different. If ore is crushed by a single explosion, the Rosin–Rammler distribution arises (Kuznetsov, 1977); in the case of multiple explosions, the Kolmogorov distribution is realized (Rodionov et al., 1986).

The cavitation melting will be the most efficient if the distribution of cavitation bubbles by size at the moment of shock loading is consistent with the distribution of ore microparticles. The revealed universal relationship (2) between the radius of a microparticle completely melted by interaction and the bubble radius  $>r_0$  makes it possible to obtain readily the type of bubble size distribution required to fit the distribution of microparticles, which, if necessary, can be changed, for instance, in a mill or by multiple explosions.

In conclusion, it should be noted that the cavitation chamber may be filled with chemically active, gold-dissolving working liquids in order to combine the cavitation melting with the currently applied chemical methods of gold recovery from ore.

## CONCLUSIONS

This study continues investigations of the mechanisms responsible for the formation of mineral nano- and microparticles under the effect of cavitation in a host liquid (Adushkin et al., 2004a, 2004b, 2006). The mechanism of cavitation melting of mineral microparticles in gold ore is considered in this paper. Universal relationship (2) connects the maximum radius of a microparticle completely melted in the process of bubble collapse with the initial radius of the bubble. It has been shown that cavitation melting is a threshold process with respect to the ambient pressure; the threshold  $P_0$  has been determined for the minerals under study. The pressure induced by melting of a gold nucleus

incorporated into a quartz microparticle has been estimated. It was shown that the melting of the gold nucleus gives rise to the breakup of the quartz shell. A conceptual design of a cavitation device intended for breakup of gold-bearing particles is proposed. Methods of optimizing implementation of this device for processing of gold ore from particular deposits have been indicated.

#### ACKNOWLEDGMENTS

This study was supported by the Division of Earth Sciences, Russian Academy of Sciences (the basic research program "Nanoparticles in Natural and Technogenic Systems"), and by the Russian Science Support Foundation (the program "Doctors of Science of the Russian Academy of Sciences").

#### REFERENCES

1. V. V. Adushkin, S. N. Andreev, and S. I. Popel, "Cavitation Mechanism of Formation of Nano- and Microsize Particles in Ore Deposits," *Geol. Rudn. Mestor.* **46** (5), 363–370 (2004a) [*Geol. Ore Deposits* **46** (5), 313–320 (2004a)].
2. V. V. Adushkin, S. N. Andreev, and S. I. Popel, "Cavitation Mechanism of Nano- and Microparticles Formation in the Earth's Interior," *Dokl. Akad. Nauk* **399** (1), 107–109 (2004b) [*Dokl. Earth Sci.* **399** (8), 1153–1155 (2004b)].
3. V. V. Adushkin, S. N. Andreev, and S. I. Popel, "Formation of Nano- and Microspherules of Minerals in Ore Deposits Depending upon Depth of Host Rock Occurrence," *Geol. Rudn. Mestor.* **48** (3), 237–243 (2006) [*Geol. Ore Deposits* **48** (3), 237–245 (2006)].
4. G. N. Gamyanin, Yu. Ya. Zhdanov, and A. S. Syromyatnikova, "Composition and Structural Features of Endogenic Spheroids in Gold Deposits, Northeastern Russia," *Zap. Vseross. Miner. O-va* **128** (5), 71–75 (1999).
5. V. M. Kuznetsov, *Mathematical Models of Blasting* (Nauka, Moscow, 1997) [in Russian].
6. M. A. Margulis, "Sonoluminescence," *UFN* **170** (3), 263–287 (2000).
7. E. M. Nekrasov, *Foreign Endogenic Gold Deposits* (Nedra, Moscow, 1988) [in Russian].
8. M. I. Novgorodova, G. N. Gamyanin, Yu. Ya. Zhdanov, et al., "Microspherules of Aluminosilicate Glass in Gold Ores," *Geokhimiya* **41** (1), 83–93 (2003a) [*Geochem. Int.* **41** (1), 76–85 (2003a)].
9. M. I. Novgorodova, S. N. Andreev, A. A. Samokhin, and G. N. Gamyanin, "Cavitation Effects in the Formation of Mineral Microspherules in Hydrothermal Solutions," *Dokl. Akad. Nauk* **389** (3), 669–671 (2003b) [*Dokl. Earth Sci.* **389** (3), 429–431 (2003b)].
10. V. N. Rodionov, I. A. Sizov, and V. M. Tsvetkov, *Principles of Geomechanics* (Nedra, Moscow, 1986) [in Russian].
11. G. V. Foss, *Gold* (Gosgeoltekhizdat, Leningrad, 1963) [in Russian].