Cavitation conditions in the molten metal under the action of the disk agitator

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Abstract. This work investigates the conditions for cavitation in molten metal under the action of a mixing device. An estimate of the rotational speed of the agitator is made, at which the cavitation number becomes less than unity. The dependence of the limiting amplitude of the longitudinal oscillations on the oscillation frequency, above which cavitation takes place, has been obtained on the basis of a numerical simulation of the turbulent flow of an incompressible fluid in a crucible, caused by the action of vibrating agitator. It is shown that the bubbles of saturated metal vapors are mainly formed on the leeward side of the agitator elements, and the external discs of agitator are subject to the greatest cavitation effect.

1. Introduction
By now, various technologies for additional alloying and modifying industrial aluminum alloys have been developed, which have reached a certain level, and further attempts to improve them do not allow obtaining the required result [1]. An alternative method (technology) of impact on molten metal is a specially developed mixing device [2], which due to the complex action of vibration, mechanical stirring and introduction of nanoparticles of modifiers (oxides, borides, etc.) into the molten metal enables improving the quality of the metal. The device consists of a disk agitator (figure 1 a) and a source of rotation. The disk agitator consists of three perforated disks and sixteen dowels. The sizes of the holes in the disks are fitted so that when the device operates in a crucible at a melt temperature of 720-780° C, the molten metal can pass through the holes. It is known that when vibrating a mixing device immersed in a molten metal, cavitation [3] may occur, which, on the one hand, has a positive effect on the process of introducing microparticles into the molten metal [2], but on the other hand it can destroy the mixing device.

The purpose of this study is to evaluate the operating conditions of the mixing device [2], in which hydrodynamic cavitation occurs in molten aluminum under the action of a disk agitator.

2. Description of the problem
In figure 1 b the agitator is shown after 5 minutes of operation in an industrial crucible with a capacity of 100 liters with molten aluminum at a temperature of 750° C and a speed of 2500 rpm. As can be seen from the figure, all the dowels are absent. The edges of the disks are "eaten". Considering that the melting point of titanium, from which the agitator is made, is about 1670° C, the temperature influence of molten aluminum can’t cause the destruction of the agitator. In addition, the structure of the surface of the disk agitator is typical for a surface that has been subjected to cavitation.
Cavitation occurs when fluid flows around poorly streamlined bodies, when the static pressure in the liquid is less than the partial pressure of saturated vapors and dissolved gases. The conditions for the appearance of hydrodynamic cavitation correspond to the cavitation criterion determined by the expression [1, 3]:

$$\kappa = \left[ P_1 - P_{sv}(T) \right] (0.5 \rho V^2)^{-1},$$

where $\rho$ is the density of the liquid metal, $V$ is the velocity of the liquid metal, $P_1$ is the static pressure; and $P_{sv}$ is the pressure of the saturated vapor of the metal at a temperature $T$, which obeys the law: [4]:

$$P_{sv}(T) = P_1 \cdot \exp \left[ LR_u^{-1} \left( T_{boil}^{-1} - T^{-1} \right) \right]$$

It is known that hydrodynamic cavitation occurs when the value of the cavitation criterion is less than unity.

3. Influence of rotational speed

Let us take the heat of evaporation of aluminum $L = 2.943 \cdot 10^5$ J/(mol), and the boiling point of aluminum under normal conditions $T_{boil} = 2723$ K [4]. Here the universal gas constant is $R_u = 8.31$ J/(mol·K), and atmospheric pressure $P_1 = 101325$ Pa. Assume that the temperature of molten aluminum is $750^\circ$ C ($T = 1023$ K), the density of liquid aluminum is $2700$ kg/m$^3$, and the outer radius of the agitator disk is $R$. At a rotational speed of the stirrer per minute $n$, the angular velocity is equal to $2\pi n/60$, and the circumferential speed of the edge of disk is $2\pi n R/60$. Then the number of revolutions at which cavitation occurs is determined by the inequality:

$$n > n_c(T, R) = 60 \left( \frac{2\pi R}{10^3} \right)^{-1} \left[ 2\rho^{-1} (P_1 - P_{sv}(T)) \right]^{0.5}.$$

Figure 2 shows the dependence of the critical speed on the temperature of molten aluminum. The region lying above the curve is the region where cavitation occurs, and below is the absence of cavitation. For a disk radius of 40 mm, a speed of rotation above 2100 rpm leads to cavitation at any temperature values, and for a disk radius of 75 mm, this is a speed above 1100 rpm.

Figure 3 shows the dependence of the critical speed on the radius of the agitator disk. The region lying above the curve corresponds to the region of cavitation origin, and the one below – to the absence of cavitation. When the temperature of aluminum changes from the melting point from $660^\circ$ C to $2000^\circ$ C, the position of the curve for the dependence of the critical speed of the stirrer on the radius of the disk varies slightly, and at high temperatures of $2200^\circ$ C and above, the shift of this curve becomes noticeable. It can be seen from the graph that for a disk radius of less than 26 mm – 27 mm cavitation will not occur when the temperature varies from $660$° C to $2000$° C.

4. Influence of vibration

It is known that the areas of reduced pressure appear in the molten metal near the surface of the
vibrator oscillating at certain frequencies and amplitudes, where the pressure becomes less than the saturated vapor pressure of metal [5]. In these areas vapor bubbles are formed, and at their collapse high pressure develops and destroys the surface of the vibrator, i.e. the phenomenon of cavitation occurs.

Figure 2. Dependence of critical revolution number on metal temperature.
1 – $r = 0.075$ m, 2 – 0.04 m

Figure 3. Dependence of critical revolution number on disk radius.
1 – $T = 660^\circ$ C, 2 – 2000$^\circ$ C, 3 – 2200$^\circ$ C

To study the conditions for the appearance of the phenomenon of cavitation one can analyze the flow of molten metal in a cylindrical crucible CABD (figure 4) under the action of vibrator 2 harmonically oscillating along the guide rod 1 by the law $x = A \cos(\omega t)$. The top bound of the crucible CD is open, and the boundaries of CA, AB and BD are the solid surfaces which are impermeable to molten metal.

Figure 4. Problem domain

Figure 5. Difference grid element.

The assumptions used to describe the mathematical model are as follows: the molten metal and metal vapor are considered to be an incompressible fluid; the surface tension of a liquid metal, which is significant for bubble radii much less than 1 μm, is neglected; the flow is turbulent, axisymmetric; the vibration is low frequency one; the velocity lag of vapor bubbles in the molten metal is neglected. A set of governing equations consists of:

– mass conservation equation for the metal vapor

$$\frac{\partial \alpha \rho}{\partial t} + \nabla \cdot (\alpha \rho \vec{V}) = R_i - R_v$$

(1)
– mass conservation equation for a mixture of molten metal and metal vapors

\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{V}) = 0 \]  

(2)

– momentum equation for the mixture

\[ \frac{\partial \rho \vec{V}}{\partial t} + \nabla \cdot (\rho \vec{V} \vec{V}) = -\nabla p + \nabla \cdot \bar{\tau}_{eff} \]  

(3)

– turbulence kinetic energy equation

\[ \frac{\partial \rho k}{\partial t} + \nabla \cdot (\rho k \vec{V}) = \nabla \left[ \left( \mu + \frac{\mu_{turb}}{\sigma_k} \right) \nabla k \right] + G_k - \rho \varepsilon \]  

(4)

– turbulence dissipation rate equation

\[ \frac{\partial \rho \varepsilon}{\partial t} + \nabla \cdot (\rho \varepsilon \vec{V}) = \nabla \left[ \left( \mu + \frac{\mu_{turb}}{\sigma_{\varepsilon}} \right) \nabla \varepsilon \right] + C_{\varepsilon} \frac{\varepsilon}{k} G_k - C_{2\varepsilon} \frac{\rho \varepsilon^2}{k} , \]  

(5)

\[ \rho = \alpha_L \rho_L + (1 - \alpha_L) \rho_0 \]  

is the density of mixture; \( \rho_L \) is the density of molten metal; \( \rho_0 \) is the density of metal vapor; \( \bar{\tau}_{eff} = \bar{\tau} + \bar{\tau}_{turb} \) is the effective stress tensor; \( \bar{\tau}_{turb} = \mu_{turb} \left( \nabla \vec{V} + \nabla \vec{V}^T \right) - \frac{2}{3} \rho,k \vec{U} \) is the turbulence stress tensor; \( \bar{\tau} = \mu \left( \nabla \vec{V} + \nabla \vec{V}^T \right) \) is the viscous strain rate tensor; \( \mu = \mu_L \alpha_L + \mu_0 \left( 1 - \alpha_L \right) \) is the dynamic viscosity of mixture; \( \mu_{turb} = \rho \xi k^2 \varepsilon^{-1} \) is the turbulent viscosity; \( G_k = 2 \mu_{turb} S : S \) is the production of turbulent kinetic energy due to shear flow (gradient of speed); and \( S = 0.5 \left( \nabla \vec{V} + \nabla \vec{V}^T \right) \) is the strain tensor.

The mass transfer process from the vapor phase to the molten metal phase and back is described in accordance with the Zwart-Gerber-Belamri model [6]:

\[ R_v = f_{\text{sup}} \frac{2 \alpha_{\text{muc}} (1 - \alpha_L) \rho_0}{r_b} \left( \frac{2}{3} \frac{p_{sv}}{\rho_i} \right)^{0.5} \] , \( p < p_v \)

\[ R_v = f_{\text{cond}} \frac{2 \alpha_{\text{muc}} \alpha_L \rho_0}{r_b} \left( \frac{2}{3} \frac{p - p_{sv}}{\rho_i} \right)^{0.5} \] , \( p > p_v \)

\( p_v \) is the saturated vapor pressure; \( r_b = 10^{-6} \text{m} \) is bubbles radius, \( \alpha_{\text{muc}} = 5 \cdot 10^{-4} \) is the nucleation site volume fraction; \( f_{\text{sup}} = 50 \) is the evaporation coefficient; and \( f_{\text{cond}} = 0.01 \) is the condensation coefficient.

Calculations in (3) – (4) were carried out for the next parameter values: \( C_{1\xi} = 1.44; C_{2\xi} = 1.92; \) \( C_p = 0.09; \sigma_L = 1.0; \sigma_{\varepsilon} = 1.3. \)

No-slip conditions are set on solid surfaces of the crucible and the agitator, the atmosphere static pressure is set at the open boundary.

The solution of the mathematical model is realized with Ansys-Fluent [7]. The finite volume method is used for solving the set of governing equations (1) – (5). A set of governing equations (1)-(5) is calculated by implicit method in which the flow finite-difference scheme of the first order approximation is used for convective terms of the equations. The pressure field is calculated with the standard algorithm. Coupling the pressure and velocity is carried out with the method SIMPLE [8]. The values of turbulence variables at the solid surfaces are determined in accordance with the model.
of SWF (Standard Wall Function). To simulate the vibrator motion we used the Dynamic mesh approach with the mesh rebuilding by layers (Layering). The time step depends on the oscillation frequency of the vibrator and varies from $10^{-2}$ s to $10^{-6}$ s.

The calculations were performed on a finite difference grid consisting of 81848 quadrangular cells, which were refined near the surface of the vibrator (figure 5).

5. Results and discussion

Calculations were carried out for the following parameter values: the density of molten metal $\rho_l = 2700$ kg/m$^3$ and the vapour density of metal $\rho_v = 0.87$ kg/m$^3$; the dynamic viscosity of liquid metal $\mu_l = 10^{-3}$ Pa·s and the dynamic viscosity of a metal vapor $\mu_v = 1.8 \times 10^{-5}$ Pa·s; and $p_{SV} = 1$ Pa. The sizes of the crucible are as follows: the height CA is 0.3 m, and the diameter AB is 0.2 m.

The limit dependence of the oscillation amplitude of the vibrator $A_{lim}$ on the oscillation frequency $f = \omega/2\pi$ at which cavitation is possible is shown in figure 6. The cavitation occurs if the vibrator oscillates with a frequency $f$ and amplitude $A > A_{lim}(f)$ and otherwise does not arise.

![Figure 6. Limit dependence of the amplitude of oscillation on the frequency.](image)

![Figure 7. Bubble formation of vapor metal.](image)

The results of numerical simulation are denoted by the symbols and approximated by a curve $A = 1371 \cdot f^{-0.5}$ (solid line) using the least squares method. According to the theoretical estimates of Ignat’iev et al [5] the limiting amplitude of vibrations is inversely proportional to the vibration frequency. The difference in the results may be explained by the fact that Ignat’iev does not take into account the viscosity of the molten metal when estimating the filling time of the cavity, which is of great importance in this case.
The patterns of the formation of metal vapor bubbles near the vibrator elements oscillating along the vertical axis with a frequency of 100 Hz and amplitude of 7 mm after the first oscillation period in the time interval $1 \leq u/T < 2$ are shown in figure 7. The limiting value of the oscillating amplitude of the vibrator for such a frequency is $\approx 3$ mm, at which cavitation occurs.

Metal vapor bubbles growing with time are formed at the periphery of the holes of the lower disk when the vibrator moves upwards (figure 7 b-e) and break out of the disk in the maximum up position of the vibrator, figure 7 f. The bubble sizes are comparable with the cross-sectional sizes of the vibrator elements. In addition, bubbles are formed on the elements of the middle and upper disks, the sizes of which are much smaller than the ones of the vibrator elements. They break out of the disk before the vibrator takes the maximum up position (figure 7 c-f). When the vibrator moves downward, the formation of bubbles occurs mainly on the elements of the upper disk (figure 7 g-j); and at the same time one can see small bubbles that are formed on the elements of the lower and middle disks.

6. Conclusions
The hydrodynamic cavitation is shown to be the cause of destruction of the 80 mm agitator’s disks rotating at a speed of 2500 rpm. Increasing the diameter of the disk agitator allows one to reduce the number of revolutions of the source of rotation at which cavitation occurs.

To create a cavitation effect in molten aluminium with a temperature of more than 660°C at a speed of about 1000 rpm, an agitator with a disc radius of more than 75 mm should be used.

It is shown that at a temperature of molten aluminium in the range from 660°C to 2200°C and a rotational speed of the agitator below 3000 rpm, a cavitation effect does not occur if the radius of the agitator disk is less than 26 mm.

The critical revolution number of the agitator remains constant when the molten metal temperature rises to 70% of the boiling point, after which a sharp drop in this value is observed.

According to the patterns of formation and development of bubbles obtained from the numerical simulation, the greatest cavitation impact on the surface of the vibrator should be expected at the edges of the upper and lower disks that is confirmed by the results of the experiment (figure 1 b).

The limiting amplitude of the axial vibration of the agitator, at which cavitation occurs, is obtained to be inversely proportional to the vibration frequency raised to the four-thirds power.

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References
[1] Efimov V A and El’darkhanov A S 2004 Technologies of modern metallurgy (Moscow: Novye Technologii)
[2] Vorozhtsov A B, Arkhipov V A, Shrager E R, Dammer V Ch, Vorozhtsov S A, Khmeleva M G Ustroistvo dlya smeshivaniya zhidkostey i poroshkov s zhidkostyu [Device for mixing liquids and powders with liquid]. Zayavka na patent. The patent application № 2016130836 RF / Zayavlono. Is claimed 26.07.2016
[3] Franc J-P and Michel J-M 1982 Fundamentals of Cavitation (New York: Kluwer)
[4] Nikolskiy B P 1982 Chemical Handbook vol 1 (Moscow-Leningrad: Chemistry) pp 682–93.
[5] Ignat’ev I E, Dolmatov A V, Ignat’eva E V, Istomin S A, Pastukhov E A 2012 Russian Metallurgy 2 97–101.
[6] Zwart P J, Gerber A G, Belamri T A 2004 Proc. Fifth Int. Conf. on Multiphase Flow (Yokohama, Japan: Tsukuba).
[7] ANSYS FLUENT. Tutorial Guide: Release 14.0. 2011. ANSYS Inc.
[8] Patankar S 1980 Numerical heat transfer and fluid flow (Washington: Hemisphere Publ. Corp.)