IOP Conference Series: Materials Science and Engineering

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To cite this article: A Antonnikova *et al* 2016 *IOP Conf. Ser.: Mater. Sci. Eng.* **124** 012044

Analytical study of ultrasound influence on the molten metals atomization

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Abstract. This paper focuses on the study of influence of ultrasound on liquid atomization using ejection nozzles. Two principles of influence of ultrasound on the atomization process such as a change of conditions on gas-liquid boundary during the generation of ultrasound oscillation in the gas and liquid jet (film) disintegration under the action of capillary forces in cases of generation of ultrasound oscillation in the liquid are considered. The optimal values of the ultrasound oscillation frequencies are calculated. Two constructions of the nozzles patented are proposed.

1. Introduction

In metallurgy, the gas spraying technique involving ejection nozzles is widely used to produce the high-dispersive powders from molten light metals [1]. The powder obtained is a poly-dispersive one and the fine fraction yield (the size of particles is less than 10 μm) is equal to 25 %. The problem of enhancement of the fine-dispersive fraction yield is currently important due to stiffening of the obtained atomizer dispersivity requirements. Experience has shown that gas-dynamic molten metals' spraying using hot gas has a limitation of dispersivity of the obtained powders due to stability improving of the small size drops in an airflow. The increase in the obtained powders dispersivity due to increase in temperature or pressure of spraying gas is an expensive approach since the energy consumption for production of powders rises sharply [2, 3].

Work [4] shows an increase in spray dispersivity due to impact of ultrasound oscillation on the atomization process. For this purpose, the wedge connected to a resonant cavity was located in a gas path of the nozzle. During the wedge flow the ultrasound oscillation appeared in gas. This study includes the research of impact of ultrasound oscillation on the liquid spraying process and the search for engineering solutions of its application.

2. Results and discussion

2.1. *Excitation of oscillation in a gas flow*

During the movement of a liquid jet in gas, the cavitation occurs, known as spraying. The process of liquid spraying (breaking of the liquid surface to form a large number of small droplets) involves an increase of amplitude and the appearance of instability of short waves on the liquid surface in cases of a dynamic impact of the gas flow. The analysis of the problem of the liquid jet disintegration due to a high-speed blowing gas flow showed that the increment of liquid surface oscillation has a maximum at wave number value [5]

$$k_{\max} = \frac{2\pi}{\lambda_{\max}} = \frac{2}{3}\frac{\rho u_g^2}{\sigma}, \tag{1}$$

where u_g is the relative velocity of gas and a jet at liquid surface; $\lambda_{\max}$ □ is the wavelength of more instable oscillation.

Using the equation (1), it is possible to obtain the equation for frequency of oscillation of more instable short waves:

$$f_{\max} = \frac{u_g}{\lambda_{\max}} = \frac{\rho u_g^3}{3\pi\sigma}. \tag{2}$$

The maximum of increment of oscillation is achieved at frequency of oscillation of liquid surface $f_{\max}$:

$$\alpha_{\max} = 0.4\frac{u_g^3}{\sigma}\sqrt{\frac{\rho^3}{\rho_l}},$$

where ρ_l is liquid density.

During movement of gas relatively the liquid surface, the turbulent boundary layer appears in it. The wave (roughness) amplitude on liquid surface ζ and the gas velocity in flow core u (that is equal to the nozzle velocity) are linked to the gas velocity on the liquid surface by means of the equation

$$u = u_g \ln\left(\frac{\delta}{\zeta}\right), \tag{3}$$

where δ is a characteristic size of the liquid jet. The amplitude of initial disturbance on the liquid surface does not usually exceed $\zeta=10^{-2}\delta$ [3] so the gas velocity on the liquid surface is equal to $u_g = 0.217\ u$. Substituting this value in equation (1), we obtain the value of oscillation frequency that has a maximum perturbation action on the liquid jet (molten metal)

$$f = f_{\max} = 1.1\cdot 10^{-3}\frac{\rho u^3}{\sigma}. \tag{4}$$

Calculating the frequency of the maximum perturbation action on the jet of molten aluminum, we obtain value $f = 87$ kHz. This value of frequency of ultrasound oscillation agrees with the experimental results obtained for the nozzle with generating of oscillation in gas using a resonant cavity [4].

The oscillation of the elastic plate in a blowing gas flow can be used to generate the ultrasound oscillation in gas (in addition to the resonant cavity). During gas movement the plate begins to oscillate with its own frequency determined by its sizes and physical properties of the material [6]:

$$f = \pi^2\sqrt{\frac{D}{\rho_p h}\left\{\frac{G_x^4}{b^4} + \frac{2}{a^2b^2}[\nu H_x H_y + (1-\nu)J_x J_y]\right\}}, \tag{5}$$

where $D = \frac{Eh^3}{12(1-\nu^2)}$ is cylindrical of the plate stiffness; E is the elasticity modulus of the material of a plate; ν is the Poisson number; ρ_p is the density of the material of the plate; *a, b, h* are the length, width and thickness of the plate; G_x, G_y, H_x, H_y ,J_x, J_y are the coefficients depending on the conditions of plate fixing and the mode of oscillations.

For longitudinal oscillation of the plate that is clamped at one end and the first mode, the equation (5) is simplified as (G_x=0.597, $H_x = -0.087$, $G_y = H_y = 0$, J_x= 0.471, J_y= $12/\pi^2$) and is given by

$$f = \pi^2\sqrt{\frac{Eh^2}{12(1-\nu^2)\rho_p}\left[\frac{G_x^4}{a^4} + \frac{2}{a^2b^2}(1-\nu)J_x J_y\right]}. \tag{6}$$

For practical calculations the formula (6) can be converted into the following:

$$f = \frac{h}{a^2}\sqrt{\frac{E}{(1-v^2)\rho_p}\left[1+9(1-v)\frac{a^2}{b^2}\right]}. \tag{7}$$

Varying the material of the plate (E, ρ_p, ν) and its geometrical sizes (a, b, h), we can state that the frequency range of free oscillation of the plate was in the range of frequency close to the frequency of the maximum perturbation action on the surface of the liquid jet (4). This is the reason of effective liquid jet disintegration (spraying).

The calculated values of sizes of the plate from steel 1X18H9T ensuring its own oscillations with frequency 87 kHz are equal to the following: length $a = 25$ mm, width $b = 12$ mm and thickness $h = 1.92$ mm. Figure 1 shows the construction of the nozzle with six plates of the mentioned sizes [7].

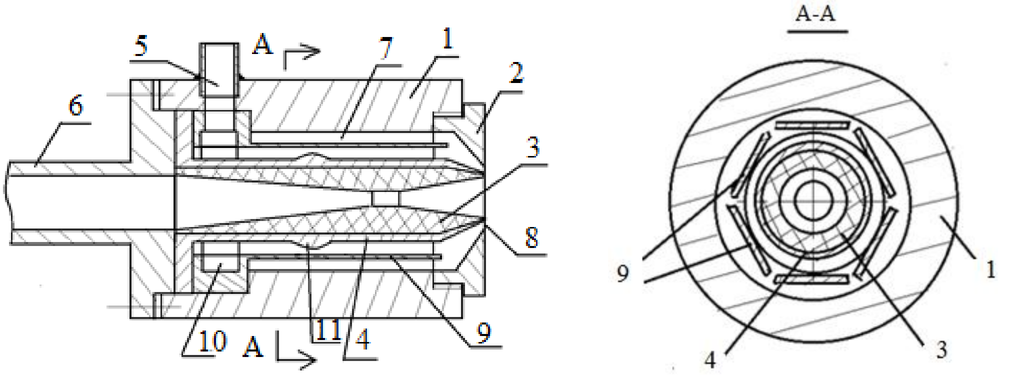

Figure 1. Construction of the nozzle with perturbation of ultrasound oscillations in a gas flow: 1 – nozzle body; 2 – head; 3 – nipple for fuel injection; 4 – metal barrel; 5 – gas port; 6 –metal supply pipe; 7 – gas cavity; 8 – annular nozzle; 9 – plates; 10 – annular cavity; 11 – boss.

2.2. *Excitation of oscillation in the liquid film*

The surface energy of the liquid jet is not minimal, thus small perturbations acting on the liquid surface are enhanced by capillary forces. It results in disintegration of the jet to the droplets. The analysis of the problem on the liquid jet (film) disintegration under the action of capillary forces has shown [5] that an increment of oscillations of the liquid surface has a maximum at wave number value $k=2\pi/\lambda$ (where λ is the wavelength) that is equal to

$$k = k_{\max} = \left[2\delta^2 + \frac{\mu\delta}{\rho}\sqrt{\frac{\rho\delta}{2\sigma}}\right]^{-\frac{1}{2}}, \tag{8}$$

where δ is the liquid film thickness; μ is the factor of the dynamic viscosity of the liquid; ρ is the density of the liquid; σ is the surface tension factor of the liquid.

From equation (8), we can find the equation for wavelength:

$$\lambda_{\max} = 2\pi\left[2\delta^2 + \frac{\mu\delta}{\rho}\sqrt{\frac{\rho\delta}{2\sigma}}\right]^{\frac{1}{2}}. \tag{9}$$

Substituting the ratio among wavelength, oscillation frequency and velocity of the liquid in equation (9)

$$\lambda_{\max} = \frac{u}{f_{\max}},$$

we obtain the equation for oscillation frequency that ensures the best conditions for the film liquid disintegration:

$$f = \frac{u}{2\pi\delta}\left[2 + \sqrt{\frac{\mu^2}{2\sigma\rho\delta}}\right]^{-\frac{1}{2}}. \tag{10}$$

The calculations of oscillation frequency that ensures the best conditions for disintegration of the molten aluminum film with the thickness of δ=0.5 mm moving at velocity equal to u=5 m/s give the value f=1.1 kHz. Figure 2 shows the construction of the nozzle acting under the impact of ultrasound on molten metal [8].

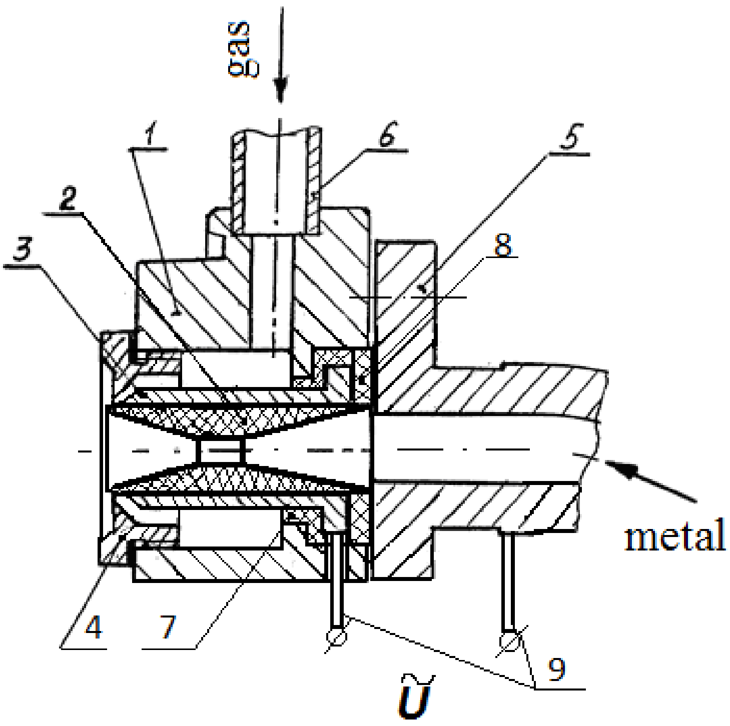

Figure 2. Construction of the nozzle with perturbation of ultrasound oscillations in the jet of molten metal: 1 – nozzle body; 2 – piezoceramic nipple for molten metal injection; 3 – metal barrel; 4 – head; 5 –metal supply pipe; 6 – gas port; 7, 8 – ceramic insulators; 9 – electrodes for alternating voltage supply.

Molten metal moving in the central canal of the spinning nozzle 2 (Figure 2) is mechanically affected by piezoceramic with frequency determined by external variable-voltage generator *U*. Spreading over the exhaust section of the spinning nozzle, the molten metal forms the film that breaks into droplets under the action of ultrasound oscillations and moves to the pulverization zone.

3. Conclusion

Using the analysis of liquid jet disintegration by the capillary forces action and high-velocity gas flow blowing, the frequencies of ultrasound oscillations influencing significantly the disintegration process are calculated. Based on the research findings, the constructions of nozzles using the ultrasound oscillations for an increase of the molten metal dispersivity are offered.

Acknowledgments

This study was funded by grant from the Russian Science Foundation (Project No. 15-19-10014).

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