Journal
of Achievements in Materials and Manufacturing Engineering

VOLUME 55
ISSUE 2
December
2012

Structural parameters compared to piezoceramic power head efficiency used in sound amplification of liquid steel

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Received 11.10.2012; published in revised form 01.12.2012

Manufacturing and processing

ABSTRACT

Purpose: The main purpose of the study was to determine the efficiency of mechanoacoustic piezoceramic power head with resonance frequency of 26.4 kHz, used in acoustic processing of liquid steel. The efficiency was determined due to compressive force quantity of piezoelectrical ceramic, characterized by the moment turning circumferential screws of the head.

Design/methodology/approach: The research was conducted on a water model. Efficiency was determined depending on the pressure force of active and passive part of the head, specified by torque moment within the range of 25-35 Nm and depending on the medium active power on the output of the generator within the range of 50-150 W. The mechanoacoustic efficiency was determined by calorimetrical method.

Findings: The acquired findings indicate relations between the radiation power inflicted, the force turning circumferential screws and the mechanoacoustic efficiency of power head.

Research limitations/implications: The results obtained shall be used while designing and operating power heads.

Practical implications: It is necessary to consider the mechanoacoustic efficiency of the applied power head during sound amplification of liquid centers.

Originality/value: Acoustic processing may be the last stage of steel ingot quality forming process, therefore it is necessary to learn all the parameters influencing its efficiency.

Keywords: Mechanoacoustic efficiency; Piezoceramic power head; Torsional moment

Reference to this paper should be given in the following way:
K. Nowacki, T. Lis, H. Kania, Structural parameters compared to piezoceramic power head efficiency used in sound amplification of liquid steel, Journal of Achievements in Materials and Manufacturing Engineering 55/2 (2012) 753-758.

1. Introduction

Ultrasonic solutions are applied in numerous spheres of science, medicine and industry. The industrial applications are often connected with the field of sonochemistry which deals with application of such devices as power heads fabricated based on piezoelectric ceramics.

Conducted studies of liquid metals sound amplifications in the ingot mould are to improve chemical homogeneity, fragmentation of original structure and hardness increase. Acoustic processing is conducted with the use of power heads built for this purpose, finished with e.g. waveguide submerged in liquid metal.

The available power generators activating those heads provide the user with no information on the power delivered to the medium being sound amplified but only with data on the generator's output parameters, such as electric power for instance. However, in order to be able to correctly control sonochemical processes, the user must know the actual energy delivered to the sound amplified medium which is conditional upon a series of parameters (e.g. damping coefficient, acoustic impedance, etc.) of the head's structural materials and the medium being sound amplified as well as design parameters of the power head itself.

The main function of a piezoelectric converter is electric energy conversion into energy of mechanical vibrations. Fig. 1 presents schematically typical ultrasound power converter (power head) used during acoustic processing of liquid steel.

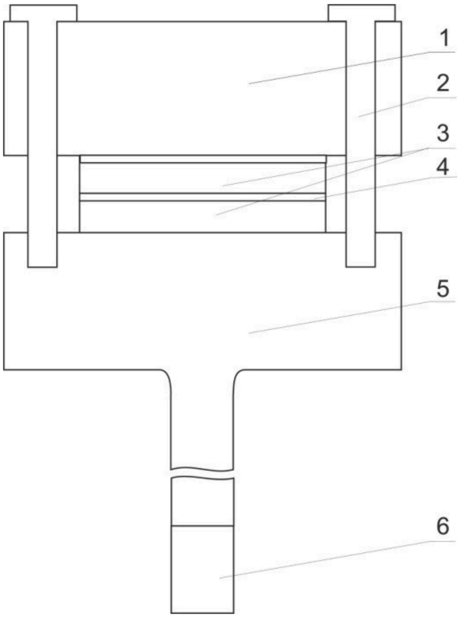

Fig. 1. Ultrasonic power head; 1 – backing, 2 – screws, 3 – piezoelectric ceramics, 4 – electrodes, 5 – radiator, 6 – waveguide

The converter's active element comprises two piezoelectric ceramic plates arranged in a stack. Such an arrangement involves the necessity of placing electrodes between the ceramic components to supply electric energy. Since the individual ceramic plates are characterised by resonant frequency of a megahertz order as well as small vibration amplitude, they are additionally loaded with masses. The resonant frequency of such a system is smaller, and hence on identical energy, it causes the vibration amplitude to rise. The aforementioned masses are referred to as passive masses, a radiant and a loading one. Together with the piezoelectric ceramic components, all these elements form a unit bound by initial stress obtained by means of a screw. Additionally, the converter includes electrodes along with conductors supplying voltage from a power generator.

Ultrasonic power converters are assumed to introduce as much energy as possible to the medium. This is possible provided that the vibrations of the radiant surface are piston-like vibrations which means that the converter is unimodular. If there are also other frequencies during the converter operation besides the fundamental frequency (higher vibration modes) then such a converter is referred to as multimodal, although it should be noted that higher modes emit lower energy.

While building a converter, the initial stress is among the important factors to be taken into consideration. One usually uses a structure featuring a central screw (Fig. 2A). Such a converter is easy to build and its dimensions are rather small, however, it also has a flaw, namely the necessity of using ceramic pieces with a hole which leads to active surface losses. A design used far less frequently is one featuring screws placed on the converter's circumference (Fig. 2B). It is more difficult to construct due to the necessity of using an identical torsional moment on each of the screws as well as larger dimensions one is forced to apply. Its advantages include the possibility of using full ceramic components of larger active surface and more uniformly arranged stresses on the ceramic components' surface.

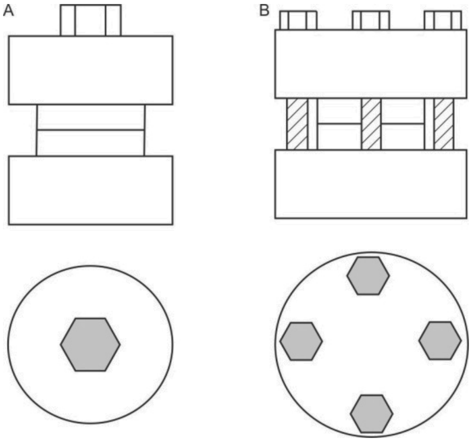

Fig. 2. Converter with (A) central and (B) circumferential stress (applied by a bolting screw)

Piezoceramic power heads are widely used in scientific research and advanced technologies. The range of impact of an acoustic wave generated by a power head covers at least the area of an ultrasonic field in which waves propagate, and this range often happens to be more than 2 times larger. The said impact may consist in both generation of new processes as well as intensification of those already in progress in the medium subject to sound amplification. The primary mechanism of the changes taking place involves the fundamental quantities of an acoustic field (e.g. periodical acoustic pressure and radiation pressure), whereas the secondary mechanism comprises the cavitation field emerging in the liquid. Ultrasounds generated with a power head have contributed to development of such areas of expertise as sonochemistry, sonoluminescence, coagulation and dispergation, ultrasonic cleaning, processing and moulding of hard media, bonding and soldering, extraction and drying, medical diagnostics [1-5].

Publications [6-9] provide results of studies concerning efficiency of a power head used in various systems and sound amplified media, for instance water or toluene. However, authors of numerous publications do not make a reference to ultrasonic efficiency of a power head depending on a crucial structural parameter, namely the system's rigidity also referred to as torsional moment (pressing force) of the screws bolting the entire system.

2. Radiation efficiency

The efficiency of energy flow from the inducing source of electric power (generator) to the medium loading the head is considered as follows [2]:

- electromechanical efficiency η_{em} determining the ratio between energy or power of mechanical vibrations P_m and energy (power) P_e received from the acoustic power source

$$\eta_{em} = \frac{P_m}{P_e} \tag{1}$$

- mechanical-acoustic efficiency η_{ma} determining the ratio between radiation power P_a and mechanical power of vibrating converter P_m

$$\eta_{ma} = \frac{P_a}{P_m} \tag{2}$$

A product of electromechanical and mechanical-acoustic efficiency is radiation efficiency η_{ea} also referred to as electroacoustic efficiency of a converter.

$$\eta_{ea} = \frac{P_m}{P_e} \cdot \frac{P_a}{P_m} = \frac{P_a}{P_e} = \eta_{em} \cdot \eta_{ma} \tag{3}$$

In order to determine the radiation efficiency, one must take all the radiation power limitations into consideration, the most crucial ones being:

- thermal limitations,
- limit of material elasticity,
- electric limitations,
- cavitation.

While the head is operating, the power emitted from the load conductance is radiated outside in the form of an ultrasonic wave, whereas the power emitted from other components of the parallel system is the power of losses, and hence in accordance with the principle of entropy increase, it is transformed into heat. These losses cause the temperature to rise, thus increasing the molecular mobility. When the temperature exceeds the Curie point, dielectric permittivity suddenly drops.

According to Hooke‘s law, deformation must be proportional to the deforming force, otherwise, when the limit of proportionality is exceeded, plastic strain occurs. Within a single period of vibrations, deflection occurs twice in opposite directions. Therefore, if the limit of elasticity is exceeded, the piezoelectric ceramic components crack after a small number of vibrations.

The high voltage delivered to the electrodes of the piezoelectric ceramic components of the power head may cause a breakdown of the dielectric forming the converter. However, under normal operating conditions, it is more likely that the limit of elasticity is exceeded first, causing the ceramics to crack.

A very significant reason for limiting the acoustic head radiation power is cavitation. When the pressure in the boundary between the head's surface and the liquid loading the former becomes lower than the saturated vapour pressure, a stream of the same liquid is detached. This phenomenon, while occurring not in the head itself but in the loading liquid, decreases the coupling between the head's radiant surface and the liquid, thus leading to a drop in the radiation efficiency.

The foregoing radiation power limitations discussed imply the necessity of undertaking further studies aimed at determination of electroacoustic efficiency of ultrasonic converters being used under specific conditions.

3. Author's own studies

The acoustic efficiency studies were conducted using a piezoelectric head bolted with six M8 screws in the circumference. The radiant part and the loading part were made of steel, and the induced element comprised two piezoceramic disks, 50 mm in diameter and 10 mm in thickness, manufactured by Ferroperm Piezoceramics (under commercial symbol Pz46). According to the manufacturer, the piezoceramic components were characterised by the following properties: density of 6.55 kg/m^3, Curie point of 823 K, sound propagation velocity of 4,300 m/s, mechanical quality factor above 2,000, dielectric constant of 120, electromechanical coupling coefficient of 0.03. The head's geometric dimensions were determined based on a system having distributed constants, by applying the Langevin equation being a simplified form of the "sandwich" converter equation [3, 10]. The head's resonant frequency equalled 26.4 Hz. The measuring apparatus also included a power generator featuring a frequency analyser and an electric power meter. Each time the experiment was conducted, the head was immersed in water to the depth of 10 mm. The cubic capacity of the glass vessel used was 800 ml. The sound amplification time was 300 seconds. The water temperature was measured using a K-type thermocouple connected with a digital meter.

The methodology applied in order to establish the power head's radiation efficiency was calorimetry [11]. The studies were conducted on a water model. Water is the most common factor forming liquid steel, because several its physical properties, in particular kinematic viscosity in room temperature is similar to viscosity of liquid steel in temperature 1873K. The head's acoustic power was established based on the following relation:

$$P_a = \frac{E_a}{t} \qquad (4)$$

where:
E_a – acoustic energy, J;
t – sound amplification time, s.

The acoustic energy marked as E_a was established based on the following equation:

$$E_a = R_n(T_2 - T_1) + m_{wo} \cdot c_{wo}(T_2 - T_1) \qquad (5)$$

where:
T_1 – water temperature prior to sound amplification, K;
T_2 – water temperature after sound amplification, K;
m_{wo} – water weight, kg;
c_{wo} – water specific heat, J/(kg·K);
R_n – vessel calorimetric equivalent.

Calorimetric equivalent R_n was established based on the following equation:

$$R_n = m_n \cdot c_n \qquad (6)$$

where:
m_n – vessel weight, kg;
c_n – vessel specific heat, J/(kg·K).

Radiation efficiency η_{ea} was established based on equation (3). For P_e, the given average active power at the generator's outlet was assumed. The study was conducted for P_e = 50, 100 and 150 W and for the stressing screws' torsional moment of M = 25, 30 and 35 Nm. For each instance of P_e and M, 10 measurements were conducted.

The average values of the results obtained have been provided in Table 1. Depending on the given average active power and the screws' torsional moment in the head's circumference, the graphical representations of the results obtained have been provided in Figs. 3 and 4.

Table 1.
Average mechanical-acoustic efficiency of a power head

Average active power P_e, W	Torsional moment M, Nm	Mechanical-acoustic efficiency η_{ea}	Standard deviation
50	25	0.792	0.07
	30	0.797	0.04
	35	0.867	0.03
100	25	0.696	0.05
	30	0.748	0.03
	35	0.788	0.08
150	25	0.672	0.09
	30	0.725	0.02
	35	0.750	0.06

Based on the results obtained, it has been determined that a larger torsional moment of stressing screws contributes to an increase in the head's mechanical-acoustic efficiency (Fig. 3).

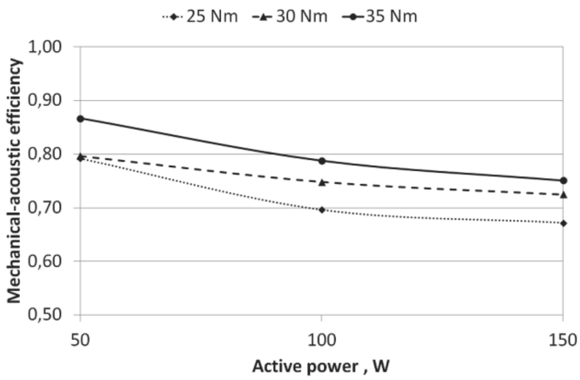

Fig. 3. Mechanical-acoustic efficiency of a power head of the circumferential screws' torsional moment of 25, 30 and 35 Nm in the function of active power at the generator's outlet

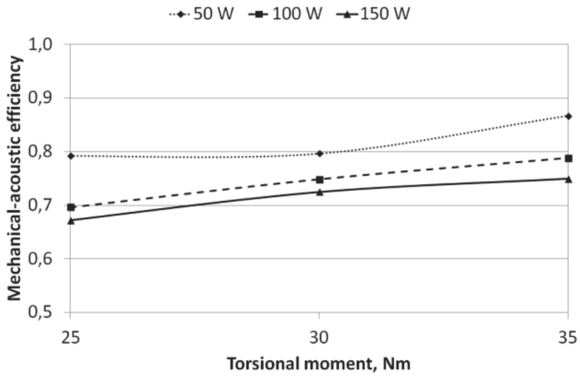

Fig. 4. Mechanical-acoustic efficiency of a power head in the function of the circumferential screws' torsional moment for three variants of average active power at the generator's outlet (50, 100, 150 W)

This trend was observed for all three cases analysed. The dependence discussed is due to an increased rigidity of the mechanical system. However, one should also entail the compression strength of the piezoelectric ceramics and the screws. Exceeding one of the aforementioned mechanical properties may cause permanent damage to the head, as in both cases the ceramic components may crack. In the course of the studies discussed, experiments including a lower torsional moment (20 Nm) were also conducted, however, the results obtained were not repeatable and implied too small mechanical rigidity of the system which caused additional issues related to the generator power control. In the case being analysed, the given P_e controlled by means of current voltage U was established based on relation (7).

$$P_e = U \cdot I \cdot \cos\varphi \qquad (7)$$

where:
U – current voltage,
I – current intensity,
φ – phase shift between the current voltage and intensity.

Small mechanical rigidity of the head caused considerable deviations of φ which then hindered effective control of the head operation within the range of the given P_e. Based on the foregoing, it has been concluded that each power head is characterised by a minimum torsional moment of stressing screws below the value of which it is difficult to effectively control the head operation. In the case being analysed, it was found that the torsional moment should exceed 20 Nm.

In numerous sonochemical processes, besides the fixed resonant frequency of the power head operation, it is also important how the radiation power is controlled as it enables the intended outcomes to be attained in the medium subject to sound amplification. The studies conducted have led to a conclusion that as the radiation power increases, the power head's mechanical-acoustic efficiency decreases. This phenomenon is related to the temperature rise in the head which, by increasing the molecular mobility, changes the acoustic impedance (acoustic wave propagation velocity, density) of the material the head is made of, and hence affects the head's matching to the resonant frequency and the sound amplified medium. Additionally, sound amplification of liquid center caused by cavitation and accumulation of cavitation blisters on the head front or, in case of coagulating centers on the front of crystallization, cause disturbances in power supply between the head and liquid center. It was observed that volume of the gaseous phase accumulated in the head's radiant part (face) increased as the preset power rose (Fig. 5). The phenomenon observed reduces the coupling between the head and the sound amplified liquid.

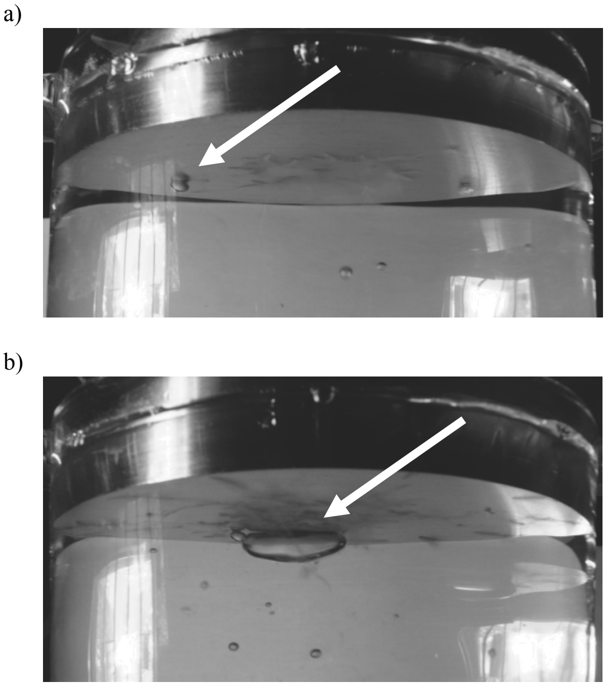

Fig. 5. Gaseous areas forming in the front surface of the power head after ca. 180 s; a – P_e 50 W; b – P_e 150 W

The results obtained were verified with reference to the data provided in publications. Owing to comparable P_e and resonant frequencies f_r of the heads examined, the reference point was assumed to be a publication of Lin, Zang [1] which, among other data, included results of head efficiency measurements for P_e of 40, 50 and 80 W and f_r of 20.1-20.2 kHz. The results published for P_e of 50 W and f_r of 20.1 kHz imply the head's efficiency of 0.87. It is practically an identical efficiency as the one obtained in the course of the studies being discussed (0.867) for a head of P_e of 50 W and M of 35 Nm.

4. Summary

Adequate operating of sonochemical processes, which include acoustic processing of liquid metals, requires knowledge on real power supplied to the hypersonic center.

The studies of mechanical-acoustic efficiency conducted by application of a calorimetric method for a power head circumferentially bolted with 6 M8 screws, characterised by the following parameters: f_r – 26.4 kHz, P_e – 50-150 W, M – 25-35 Nm, led to a conclusion that within the range of values studied:

- average power head mechanical-acoustic efficiency assumed a value between 0.672 and 0.867;
- increasing the circumferential screws' torsional moment causes a decrease in the losses of the energy emitted by a piezoceramic power head;
- the torsional moment of circumferential screws of 20 Nm causes disturbances in the head operation precluding its successful control;
- as the energy delivered to the piezoceramic power head increases, the head's mechanical-acoustic efficiency drops.

Acquired findings enable to design heads to acoustic processing of liquid steel and verification of their efficiency on water models. Acquired findings constitute the basis for determining the efficiency of piezoceramical heads operation during industrial experiments. On the basis of the findings presented in the paper, it is possible to design and conduct laboratory and industrial experiments in an effective way.

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