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Stability in Position and in Temperature for a Conical and a Cylindrical Levitator

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Abstract

In this paper a comparison is made between a cylindrical and a conical inductor ("levitator") with regard to the stability in position and in temperature for a workpiece in electromagnetic levitation.

The results of the study are based on a numerical model. The validation of the numerical model is done by measurement and by a comparison with the results that are obtained after working out analytical formulations found in literature.

It is demonstrated that a cylindrical design of the levitator results in a better stability in position of the workpiece. In principle also the stability in temperature has a chance to be better for the cylindrical design. For a workpiece made of zinc however, it turns out that it is impossible to regulate a temperature of 900 °C during levitation.

Introduction

Levitation melting is a technique based on the induction of eddy currents in a metallic sample by an alternating electromagnetic flux. These eddy currents heat the sample by Joule effect. The induced currents give cause to electromagnetic Lorentz forces at the same time. When the magnetic field is generated by a suitably shaped coil, the forces may attain a sufficient magnitude to levitate the specimen. Simultaneously, the molten metal droplet deforms, due to the "magnetic pressure".

In practice the most common geometry for a levitator is a cone. In literature, however, some exceptions are mentioned [1-2]. For the evaporation of a metallic workpiece, a cylindrical levitator is proposed [1]. In this paper it is tried to find out whether this set-up is advantageous compared to a conical levitator.

1. Comparison between a Conical and a Cylindrical Levitator

To compare a conical with a cylindrical levitator, a gradual transition is considered from the first ($\theta = 60°$) to the last geometry ($\theta = 90°$) as shown in Fig. 1. The height of the levitator is equal to 43 mm and 50 mm for θ equal to 60° and 90° respectively. The levitator consists of six coils with current inversion between the third and fourth coil. The calculations of the magnetic force are performed for θ equal to 60°, 75° and 90°. The operating frequency is 23 kHz, the current equals 1 kA, the diameter of the first coil is 45mm. The workpiece has a diameter of 12 mm and is made of zinc. The deformation due to the magnetic pressure is neglected.

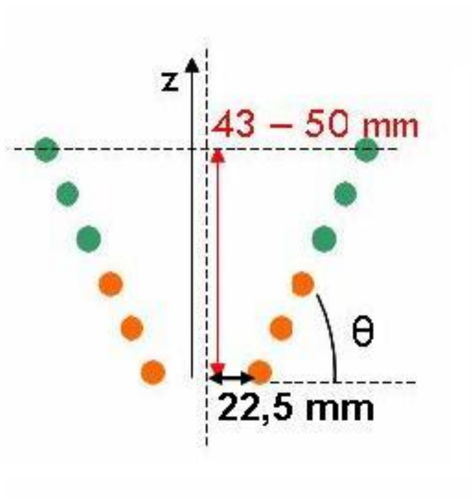

Fig. 1. Transition conical-cylindrical levitator

The calculations are performed with an electromagnetic numerical model, solved by the commercially available electromagnetic field simulation software MagNet (Infolytica). A time-harmonic solver is used to solve the Maxwell equations. The model is axisymmetric. To obtain accurate results, the two-dimensional mesh is very fine at the surface of the workpiece where the size of a triangular element of the mesh is of the order of one third of the skin depth. To validate the numerical model, the current through the levitator and the voltage over the levitator are measured and compared with the numerical results. This comparison learns that the relative error lies between 0.35% and 4%. Therefore, the numerical model can be considered as a good representation of reality.

2. Stability in Position

2.1. Calculation of the Magnetic Force

Important in the evaluation of a cylindrical levitator with respect to a conical levitator is the calculation of the magnetic force, which depends on the position of the workpiece in the levitator. Fig. 2 gives the magnetic force on the workpiece for three values of θ as a function of workpiece position (z-coordinate of Fig. 1). The discrete points are results of numerical computation, the continuous curves are analytically calculated, based on formulations found in literature [3-4].

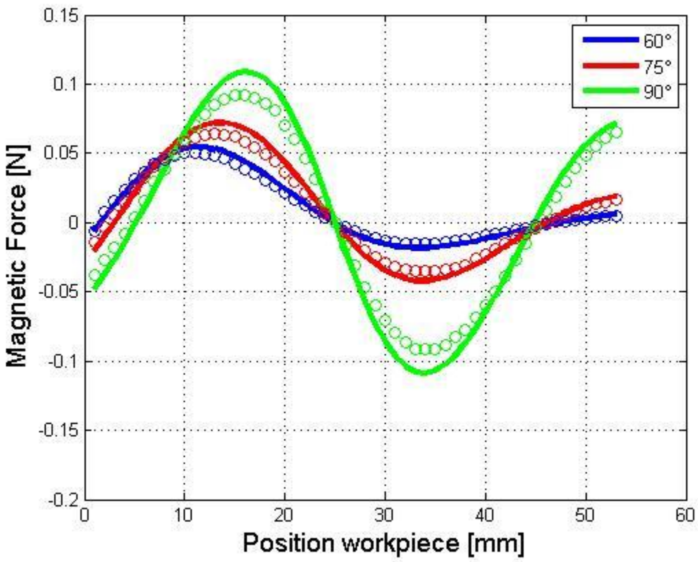

Fig. 2. Magnetic force on workpiece

For a cylindrical levitator (θ = 90°) the curve of the magnetic force has the most negative slope. In analogy with a mechanical spring, it could be stated that a cylindrical levitator is stiffer than a conical levitator.

2.2. Total Force on the Workpiece in Levitation

Two conditions must be satisfied to guarantee a stable position of the workpiece in levitation. Firstly the total force, i.e. the difference between the magnetic and gravitational force, on the workpiece must be zero. Secondly the slope of the total force as function of position must be negative. Fig. 3 shows the force on the workpiece for a cylindrical levitator (θ equal to 90°). The stable position is 22 mm. The discrete points are again the results of numerical computation, and the continuous curves are analytically calculated, based on formulations found in literature [3-4].

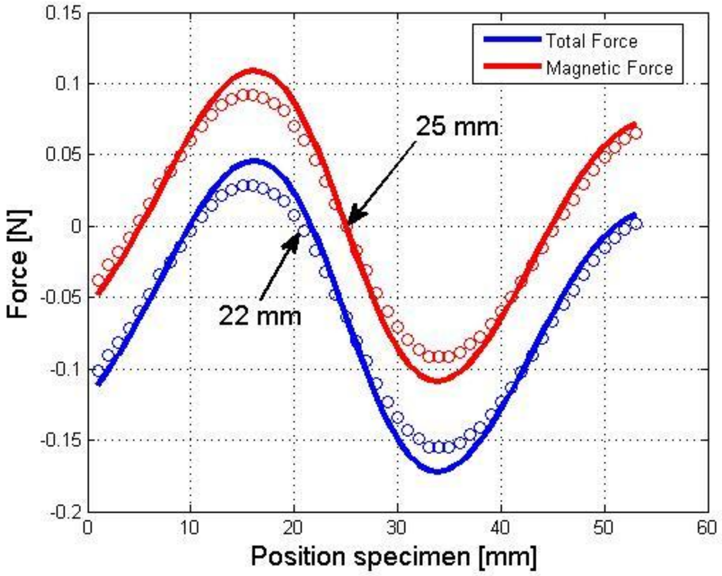

Fig. 3. Total and magnetic force on workpiece for cylindrical levitator

Taking evaporation into account, the workpiece moves between a height of 22 mm and 25 mm (theoretically 25 mm is the stable position for a massless workpiece). Therefore, it can be stated that the theoretical maximum variation in position is 3 mm.

2.3. Different Stability in Position for a Conical and a Cylindrical Levitator

It can be shown that for a conical levitator the maximum variation in position is higher than for a cylindrical levitator. An illustrative example is used to prove this assertion. Fig. 4 represents the magnetic force as a function of position.

The curve with the most negative slope gives the magnetic force for a cylindrical levitator (see also Fig. 2). In Fig. 5 the total force is represented simply by a downwards shift of the magnetic force due to the gravitational force. Fig. 5 gives the range of positions over which the workpiece moves during evaporation. The theoretical maximum of this range is limited by the stable position for a massless workpiece (Fig. 4).

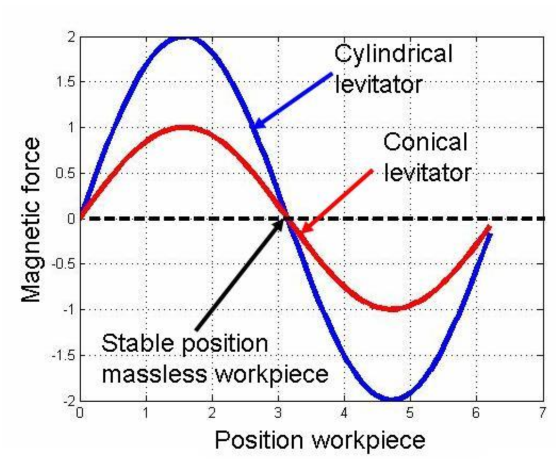

Fig. 4. Magnetic force for cylindrical and conical levitator
(position of workpiece in metrical units)

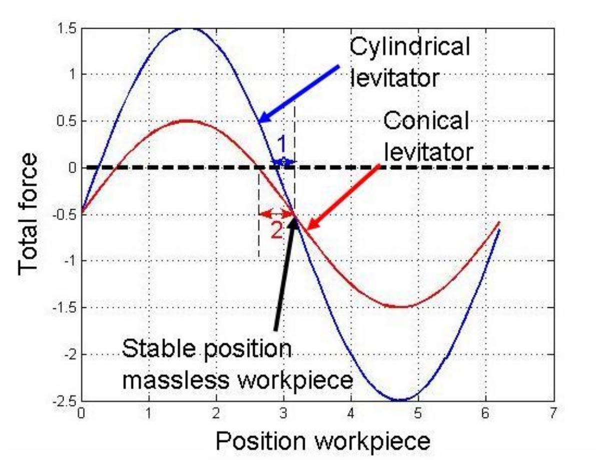

Fig. 5. Stability of the workpiece during evaporation
(position of workpiece in metrical units)

It is obvious from Fig. 5 that a cylindrical levitator is less subject to position variations during the levitation process (range 1 is smaller than range 2). This is an important advantage of the cylindrical levitator. The cylindrical levitator is intrinsically more immune against perturbations in position during evaporation. This stability in position is particularly important in the case of optical control of the workpiece.

3. Stability in Temperature

3.1. Difference in Power Dissipation between a Conical and a Cylindrical Levitator

Fig. 6 represents the power dissipation as a function of the workpiece position. The dissipation is calculated for three values of θ. The position of the workpiece corresponds to the z-coordinate in Fig. 1. The discrete points are the results of numerical computation, the continuous curves are analytically calculated with the aid of [3-4]. The three results demonstrate minimum power dissipation for a position of 25 mm. This can be explained by the current annihilation as shown by the arrows in Fig. 7.

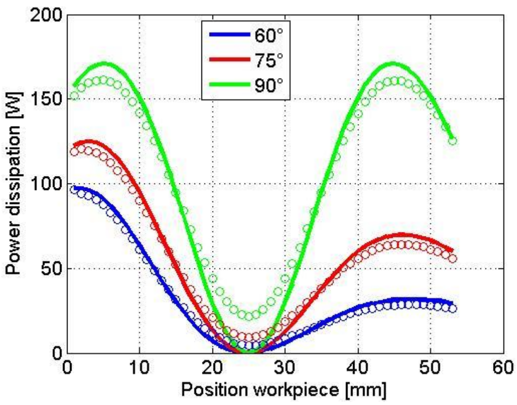

Fig. 6. Power dissipation in the workpiece

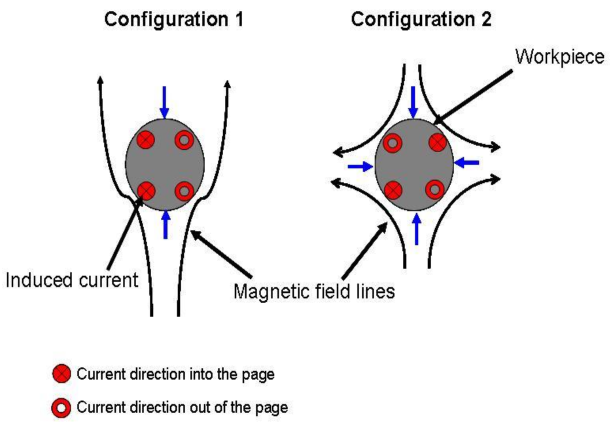

Fig.7. Current annihilation

The reason for a minimum in power dissipation for z equal to 25 mm is the configuration of the magnetic field (configuration 2 in Fig. 7). Configuration 2 in Fig. 7 represents the situation for a cylindrical levitator with current inversion. This configuration is characterized by four regions of current annihilation, which limits the power dissipation.

The first configuration in Fig. 7 is typical for a conical levitator without current inversion. The power dissipation in this case is higher because there are only two regions of current annihilation.

3.2. Power Dissipation versus Thermal Losses for a Cylindrical Levitator

As shown in the previous paragraph, power dissipation is lower for the cylindrical levitator. This lower power dissipation can be an advantage for temperature control. Indeed, for levitation in stationary regime, it is necessary to balance the power dissipation and the thermal losses. In addition to the lower power dissipation, the cylindrical levitator results in more stability in position, as proven in paragraph 4. Therefore, only the cylindrical design is considered for further investigation.

Only radiation losses are taken into account. A more complete calculation of the thermal losses can be found in [5]. The thermal radiation losses are calculated with (1). In this equation σ is the Boltzmann constant, A is the radiation surface, T_∞ equals 298 K. The temperature T of the workpiece is assumed to be homogeneous in the volume of the workpiece. The emissivity ε of zinc can vary between 0.03, for a polished surface, and 0.3 for an oxidised workpiece.

$$P_{radiation} = \sigma \varepsilon A (T^4 - T^4_\infty). \quad (1)$$

The results are plotted in Fig. 8. Note that also the power dissipation depends on the temperature of the workpiece. In Fig. 6 the value for the electrical conductivity is taken at 25 °C. When the temperature increases, the electrical conductivity decreases leading to an increasing power dissipation [3].

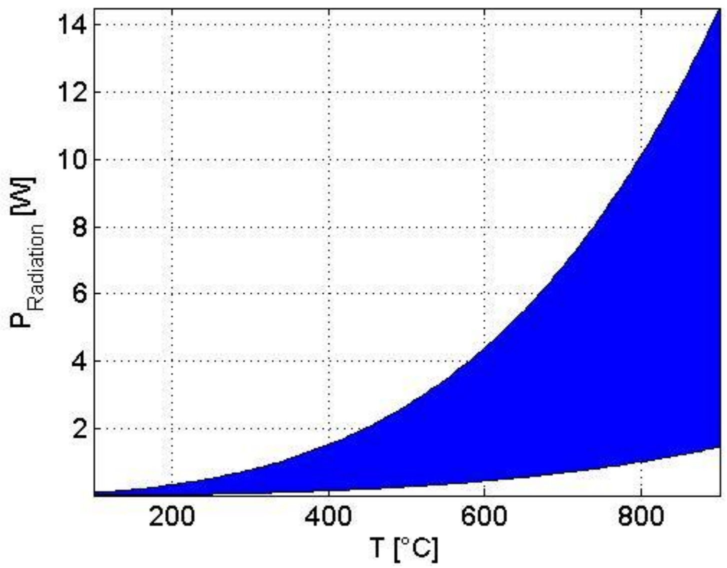

Fig. 8 Radiation losses (0.03 < ε < 0.3)

Fig. 8 learns that for a temperature of 900 °C, the thermal losses vary between 2 and 14 W. The power dissipation at z = 22 mm (stable position of the workpiece, cfr. Fig. 3) is 40 W (cfr. Fig. 6, numerical calculation for cylindrical levitator). Because of the increasing resistivity of zinc with temperature, the real power dissipation will even be higher. In any case, the power dissipation is many times higher than the thermal losses. Therefore, the workpiece will continue to heat up and temperature control is not possible.

To attain lower power dissipation, it could be an idea to reduce the frequency. However, 5 kHz is a strict minimum frequency, since the skin depth at 5 kHz is already 6 mm which approaches the 6 mm radius of the workpiece.

Conclusions

Numerical modeling results are in line with measured values and with calculations based on analytical formulations found in literature and prove that the difference between a cylindrical and conical levitator can be grasped by the notion of "stiffness" of the system. A cylindrical levitator behaves as a stiff spring and inhibits great position variations of the workpiece during levitation.

The difficulty of temperature control is demonstrated. It appears that power dissipation is many times higher than thermal losses to the environment for a temperature equal to 900 °C. As a consequence a constant temperature of 900 °C cannot be regulated for a workpiece made of zinc. It could be a matter of further investigation to study the effect of additional convective cooling for a better control of the workpiece's temperature.

References

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