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FLOWING OF THE MELT THROUGH CERAMIC FILTERS

PRETOK TALINE SKOZI KERAMIČNE FILTRE

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It is important to clean melts by filtering them with ceramic filters. Particular attention must be paid to the hydraulic conditions as the melt flows through the filter. The Bernouilli equation is used to describe the filtration of the melts. The physical regularities of the capillary melt can be seen in the flow. The Hagen-Poiseuille law and Darcy's law have been applied. The characteristics of laminar flow have been examined, as have the attributes of turbulent flow. There are dimensionless criteria characterising the melt flow through a ceramic filter. The principal mechanisms of melt filtration are assessed.

Key words: metal melt, filtration, ceramic filter, flow of metals through pores, laminar and turbulent flow

Pomembnost čiščenja kovinske taline s filtriranjem skozi keramični filter. Hidravlični pogoji pretoka taline skozi filter. Uporaba Bernouillijeve enačbe za opis filtriranja taline. Fizikalne zakonitosti kapilarnega toka taline. Hagen-Poiseuillejev in Darcyjev zakon. Značilnosti laminarnega toka. Atributi turbulentnega toka. Brezdimenzijska merila, karakteristična za pretok taline skozi keramični filter. Glavni mehanizmi filtriranja kovinskih talin.

Ključne besede: kovinska talina, filtriranje, keramični filter, pretok taline skozi pore, laminarni in turbulentni pretok

1 INTRODUCTION

Recently, many laboratory-, pilot- and industrial-scale tests were carried out in the field of filtration using the casting of cast irons and steels. The results showed that the filtration of the melts of these metallic alloys can be used advantageously in melting foundries and steel shops, using the bottom pouring of steel (i.e., ladles with a taphole at the bottom), as well as in tundish metallurgy during the continuous casting of steel, and in cases when the ceramic filter is applied directly in the entry part of the inlet system during the casting of steel and cast iron.

2 FLOWING A MELT THROUGH THE CERAMIC FILTER

The overall efficiency of filtration technology is significantly influenced by the hydraulic conditions during the flowing of the melt through a ceramic filter. The basis for the description and evaluation of the hydraulic conditions during the flowing of a metallic melt (steels and cast irons) through a ceramic filter is the Bernouilli equation, expressing the principle of the conservation of mechanical energy of the flowing liquid [1]. It is possible to express the Bernouilli law for an ideal liquid considering the individual energies in the following equation

$$\frac{\rho \cdot v^2}{2} + h \cdot \rho \cdot g + p = const.\ /\mathrm{Pa} \qquad (1)$$

in which the term $(\rho \cdot v^2/2)$/Pa represents the kinetic energy of a unit volume of liquid, the term $(h \cdot \rho \cdot g)$/Pa represents the position or gravitational energy of a unit volume of liquid, given by the earth's gravity, and the term p/Pa represents the potential pressure energy of a unit volume of liquid, which is usually dependent on externally acting forces. The individual quantities in the equation are as follows: v, the flow velocity of an ideal liquid (m s^{-1}); ρ, the density of the flowing liquid (kg m^{-3}); h, the true position, i.e., the real height of the flowing unit volume of liquid (m); g, the acceleration due to gravity (m s^{-2}); and p, the pressure of a unit volume of flowing liquid in (Pa), the basic dimensions of which are kg s^{-2} m^{-1}. According to the Bernouilli equation the sum of the kinetic, positional and pressure energies of an ideally flowing liquid remains constant at each point in the flow.

However, if this equation is to be used for a description of the flow of a real liquid, e.g., the melts of steels and cast irons, it is necessary to add to the three terms on the left-hand side of the equation one more term, i.e., e_z, which expresses the loss of energy per unit volume of a real liquid, i.e., of the melt of steel or cast iron. The loss of energy during the flow of a real liquid through the filter will be directly proportional to the kinematic viscosity of the liquid, υ (m^2 s^{-1}), to the velocity of the flowing liquid, v (m s^{-1}), indirectly proportional to the structure of the filter characterised by the length, the dimension and the geometry of the holes and capillaries in the filter, d/m, to the melt density, ρ/(kg m^{-3}), and to the dimensionless proportion constant, ξ. It is therefore necessary to express the Bernouilli equation for a filtered melt of steel or cast iron in the following form:

$$\frac{\rho \cdot v^2}{2} + h \cdot \rho \cdot g + p + e_z = const. \text{ /Pa} \qquad (2)$$

or in the explicit form

$$\frac{\rho \cdot v^2}{2} + h \cdot \rho \cdot g + p + \frac{\xi \cdot \upsilon \cdot v \cdot \rho}{\delta} = const. \text{ /Pa} \qquad (3)$$

The flow of a liquid in a round hole (i.e., in a capillary), which is characteristic for direct holes (strainer filters), is governed by the Hagen-Poiseuille law, indicating that the flow volume of a viscous liquid during laminar flow through the tube of circular cross-section is directly proportional to the hydraulic gradient, $\Delta p/\Delta l$, and the fourth power of the tube radius, and indirectly proportional to the dynamic viscosity of the flowing liquid. The Hagen-Poiseuille law is written in the form:

$$Q_V/(\text{m}^3.\text{s}^{-1}) = \frac{\pi \cdot r^4 \cdot \Delta p}{\Delta l \cdot 8\eta} \qquad (4)$$

in which Q_V is the volume of liquid flowing through the tube, r/m is the internal radius of the tube (i.e., the capillary), η/(kg m^{-1} s^{-1}) is the dynamic viscosity, Δp *is* the loss of static pressure along the length of the tube and Δl is the length of the tube. The hydraulic gradient, $(\Delta p/\Delta l)$/(kg m^{-2} s^{-2}), is in this case a measure of the liquid's resistance to flow and it is proportional to the first power of the mean velocity of the liquid flowing through the capillary.

The Hagen-Poiseuille law also determines implicitly the mean velocity of the liquid flowing through the tube. The dependence of the mean velocity of the laminar flow in a capillary can be expressed by the equation obtained by dividing the flow volume, Q_v, by the area of the cross-section of the capillary, πr^2 :

$$v/(\text{m.s}^{-1}) = \frac{r^2 \cdot \Delta p}{\Delta l \cdot 8\eta} \qquad (5)$$

It follows from this equation that the mean velocity of the laminar flow through a capillary increases with the square of the capillary's radius; it is also directly proportional to the hydraulic gradient and indirectly proportional to the octuple of the value of the dynamic viscosity.

These relations are useful for an evaluation of the hydraulic conditions during the flow of melts of steel and ductile iron through ceramic filters, because they determine the causal relations between the physical quantities that characterise the melt, such as the viscosity and the density, the geometric characteristics of the filter, such as the diameters of the holes, the filter's thickness, the parameters of the flow of the melt through the filter, such as the flow volume of the melt, its flow-rate and also its hydraulic gradient in the filter.

The Darcy law is a special case of the Hagen-Poiseuille law. It expresses the velocity of the laminar flow of a liquid in a porous environment. According to this law the velocity of the flow in a porous environment is given by the linear relation

$$v_{\text{lam}}/(\text{m s}^{-1}) = k\,\frac{\Delta p}{\Delta l} \qquad (6)$$

where k/(m^3 s kg^{-1}) is the coefficient of leakage (filtration) and $\Delta p/\Delta l$ is the already-mentioned hydraulic gradient. The Darcy law expresses the penetration of the melt into the pores in the walls of the ceramic filter's capillaries during filtration, which determines the physical-chemical reactions between the flowing melt and the filter ceramics.

2.1 Laminar flow

The laminar flow of a real liquid through the capillary is distributed in such a way that the maximum of the flow velocity is achieved in the axis of the circular section of the capillary and the minimum velocity (in practice, a zero flow velocity) near the capillary walls. The distribution of the flow velocity in the capillary in this case approaches the shape of a rotating paraboloid. This distribution of velocity occurs because the outermost layers of the liquid stick to the capillary walls, since there is great friction between the wall and the flowing liquid (in practice, an almost infinitely large friction) and due to the internal liquid friction, individual layers of liquid mutually obstruct their movement. In this way the liquid counteracts during the flow through the capillary, the passing of which requires the pressure, expressed by equations (4) to (6), related to both the mentioned laws. The laminar flow is therefore characterised for a certain mean velocity, making it possible to subsequently calculate the flow volume. During the laminar flowing of a real liquid through capillary vortex rings, vortical threads with the shape of concentric circles with the centres lying in the capillary axis, are formed [2-5].

2.2 Turbulent flow

The turbulent flow of liquids (and also gases) is the most widespread and also the most complex form of macroscopic movement of mass in technical equipment and systems. The laminar flow can only be maintained up to a critical mean velocity, because at higher mean velocities of the flowing liquid the perturbative influence of the vortices begins to prevail, the flow begins to change, the liquid threads begin to interlace and turbulent flow begins. During the turbulent flow, the resistance to flow, expressed as the hydraulic gradient, is not directly proportional to the mean velocity of the liquid flowing through the capillary, as in the case of laminar flow, but it increases approximately with its second power. Accordingly, for turbulent flow the following equation is valid for the dependence of the flow velocity of the melt through the filter and the hydraulic gradient:

$$v^{n} = \frac{\Delta p}{\Delta l} \tag{7}$$

where v is the mean velocity of the liquid flow and n is the exponent with a value approximately in the interval from 1.75 to 2.00, while for laminar flow its value is n = 1. Let us add, in connection with this, that the turbulent flow is not in accordance with the relations (4) and (5), which follow from the Hagen-Poiseuille law.

The turbulence occurs for high values of the dimensionless Reynolds number, when the following inequality is valid for this number:

$$\mathrm{Re} = \frac{v \cdot d}{\upsilon} >> 1 \tag{8}$$

where v is the characteristic velocity of liquid flow (m s^{-1}), d/m is the characteristic length dimension of the filter capillary and ν/(m^2 s^{-1}) is the kinematic viscosity.

Unlike laminar flow, turbulent flow has a large number of degrees of freedom, which results from the random vorticular movements of a large number of particles (aggregates, clusters) of liquid, i.e., turbulent vortexes. At each point of the turbulent flow of the liquid there are turbulent vortexes in the filter, which in various places of the capillary can even be formed upstream.

The velocity profile during the laminar flow of a liquid through the capillary has an approximately parabolic distribution of velocity with a distinct maximum at the capillary axis. On the other hand, the velocity profile during turbulent flow of the same liquid through the thin capillary is not parabolic, as it was for laminar flow, but the velocity is almost constant in all the internal parts of the capillary. The exception is the thin layer of liquid at the capillary wall, in which the flow velocity sharply increases from an almost zero value, approximately in proportion to the distance from the wall. The mean velocity of the turbulent flow of the liquid through the thin tube is therefore much closer to the maximum velocity than in the case of laminar flow. The gradient of the flow velocity of the liquid in the direction from the wall of a thin tube to its axis is thus greater during turbulent flow than during laminar flow, see **Figure 1**.

When the melt of steel or ductile iron flows through the strainer or foam filter, regardless of the elemental character of the flow (laminar or turbulent), there exists for both types of filter and for both types of metallic melt, i.e., steel and cast iron, a common character of contact for the flowing metallic melt with the filter walls. The velocity of the filtered metallic melt that is in contact with the filter walls is virtually zero; therefore, the melt can penetrate into the microscopic pores of both types of filter (strainer and foam filter), to a large extent in agreement with the Darcy law, as it is expressed with equation (6). Thus, it is possible to expect on the walls of the holes of the strainer filter, as well as on the walls of the irregular spaces of the foam filter, the same elementary character of physical-chemical reactions of the filtered metallic melt with the filter ceramics.

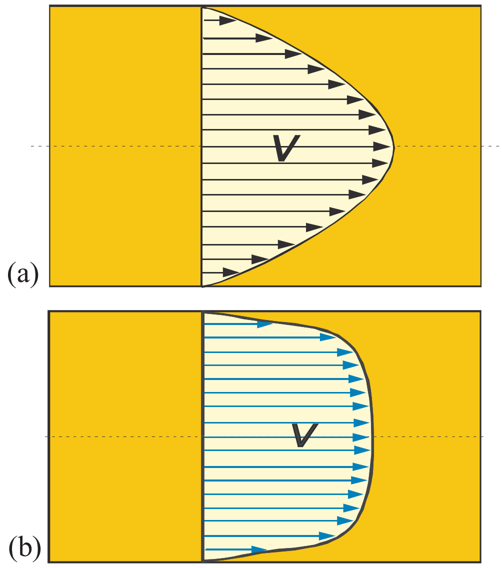

Figure 1: Profile of the velocity of laminar (a) and turbulent flow (b) of the metallic melt through a hole with a circular cross-section
Slika 1: Hitrostni profil za laminaren (a) in turbulenten (b) pretok kovinske taline skozi poro z okroglim prerezom

3 CONCLUSION

The hydraulic conditions have an important influence on the overall efficiency of the technology of filtration during the flowing of the melt through a ceramic filter. A knowledge of the hydraulic conditions during the flowing of the melts of steels and cast irons through ceramic filters, based on the physical regularities that govern the flow of metallic melts through the capillaries of ceramic filters, can be the basis for: a) the modelling of basic mechanisms for the flowing of melts of steels and cast irons through ceramic filters, b) a detailed explanation of the physical-chemical mechanisms of filtration occurring during the application of ceramic filters in the practice of foundries casting steels and cast irons, and c) the optimisation of the use of individual types of ceramic filters in the technology of the melting of steels and cast irons.

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