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Wetting and its influence on the filtration ability of ceramic foam filters

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ABSTRACT

Deep bed filtration in aqueous media is a well-known process for solid–liquid separation. However, the use of deep bed filtration for the purification of metal melts is a relatively new field of application. In particular, the separation mechanism of metal melts filtration is a new area for investigation. The current paper aims at examining the influence of wetting on the filtration efficiency of ceramic foam filters that is an important feature of the metal melts filtration process. A model system was designed using water and alumina particles (<200 μm). The particles and filter medium were coated to model poor wetting. Thus, examination of the influence of wetting on the adhesion energy and filtration performance was possible. Furthermore, the effect of fluid velocity was studied. To this end, the experiments were carried out under atmospheric conditions and at 20 °C. The findings showed that poor wetting between the fluid and solid phase significantly increased the filtration efficiency.

Introduction

Filtration of metal melts using porous ceramics has been employed in the casting industry for many decades (Ali, Apelian, & Mutharasan, 1985; Apelian, Mutharasan, & Ali, 1985; Hammerschmid & Janke, 1988). However, the separation mechanisms are not yet satisfactorily determined. Particles in metal melts originate from either crystallization reactions in the hot fluid (endogenous formation) or erosion of the furnace walls and slag entrainment (exogenous formation) (Ali et al., 1985). The particle sizes range from a few micrometers for primary endogenous particles up to a few millimeters for their agglomerates or exogenous particles. Both particle types are non-metallic, i.e., they are mainly ceramics such as alumina. Such inclusions must be avoided in the final casting because they reduce the mechanical strength and subsequently the toughness of the final product. Therefore, achieving filtration efficiencies of ~98% is important in the casting industry. To attain such high purification rates, it is necessary to analyze the filtration mechanism operating in the metal melts system via a detailed parameter study. In addition to their high processing temperature requirements and opaque nature, metal melts have a very high surface tension, which leads to poor wetting of solids in contact with the liquid phase. Thus, filtration experiments involving metal melts are very expensive and the in situ analysis of the filtration process is difficult.

To study the filtration of metal melts, it is necessary to design a model system operating under ambient conditions (20 °C and atmospheric conditions). The model system is aimed at mimicking the characteristic wetting effects of the melt system and facilitates investigation of wetting effects on filtration without the temperature effects of the real system.

Filter structures for metal melts mainly consist of ceramic materials and are available in many geometries and constructions (Ali et al., 1985; Raiber, Hantusch, Hammerschmid, & Janke, 1996; Uemura, Takahashi, Koyama, & Nitta, 1992). In this study, alumina foam filters (Emmel & Aneziris, 2012; Voigt, Jäckel, Aneziris, & Hubálková, 2013) that are produced by the Schwartzwalder process (Schwartzwalder, Somers, & Somers, 1963) were used. This enabled investigation of the filtration ability of the alumina foam filters under variable parameters such as wetting and fluid velocities.

The aims of this study are to determine the influence of wetting on deep bed filtration performance and to characterize the filtration ability of ceramic foam filters. Both processes are important for understanding and optimizing metal melts filtration processes.

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Nomenclature

c_D	buoyancy coefficient
d_C	collector diameter, m
d_P	particle diameter, m
dz	distance between particle and collector surface during contact, m
E_{adh}	adhesion energy between particle and collector, J
$E_{K,1}$	kinetic energy of particle before collision with collector, J
F_{adh}	adhesion force between particle and collector, N
F_d	detachment force acting on attached particle, N
g	gravitational constant, m/s^2
Hi	Hiller number
$m_{F,1}$	mass of filter after filtration experiment, g
$m_{F,0}$	mass of filter after cleaning, g
m_P	mass of particles introduced, g
$m_{P,r}$	mass of particles that do not flow through the filter, g
N_I	interception number
N_S	sedimentation number
Re_P	Reynolds number of particle with a certain size
Stk	Stokes number
u_L	fluid velocity, m/s
$u_{L,eff}$	effective fluid velocity relative to attached particle, m/s
$u_{L,Filter}$	mean fluid velocity in the filter, m/s
$u_{L,Pipe}$	mean fluid velocity in the pipe, m/s
$u_{P,C}$	velocity of particle near collector, m/s
$u_{P,eff}$	effective particle velocity, m/s
u_S	particle sedimentation velocity, m/s

Greek letters

ρ_P	particle density, kg/m^3
ρ_L	fluid density, kg/m^3
η_L	fluid viscosity, Pa s

Subscripts

adh	adhesion
C	collector
F	filter
eff	effective
L	liquid
norm	normalized
P	particle

Theory

Deep bed filtration is a widely accepted theory for describing metal melts filtration (Conti & Netter, 1992; Damoah & Zhang, 2010; Raiber, Hammerschmid, & Janke, 1995; Zhou et al., 2003). The filtration process can be classified into two steps: the probability of contact and the probability of adhesion. The collision between the particle and filter is described in terms of the impact of inertia, interception, and gravitation (Bao, Engh, Syvertsen, Kvithyld, & Tangstad, 2012; Ciftja, Engh, & Tangstad, 2010) as illustrated in Fig. 1(a).

The contribution of diffusion is negligible owing to the particle size that is >1 μm. The influence of gravitation is described by the sedimentation number N_S (Ives, 1975):

$$N_S = \frac{(\rho_P - \rho_L) g d_P^2}{18 u_{P,eff} \eta_L}, \tag{1}$$

$$u_{P,eff} = u_S(d_P) + u_{L,Filter}, \tag{2}$$

where ρ_P is particle density, ρ_L fluid density, g gravitational constant, d_P particle diameter, $u_{L,Filter}$ mean fluid velocity in the filter, $u_{P,eff}$ effective particle velocity, u_S particle sedimentation velocity, and η_L fluid viscosity.

Because N_S is a function of the square of the particle diameter d_P, it is mainly relevant for coarser particles. The higher the sedimentation number, the greater the contribution of gravitation on the probability of collision. The effective velocity of the particles in Eq. (2) is chosen as the characteristic velocity, which accounts for the sedimentation velocity of the particles and the mean fluid velocity within the filter structure.

Owing to the particle sizes investigated, inertia and interception are important capture mechanisms. The inertia effect is described using the Stokes number Stk, in Eq. (3) (Kasper, Schollmeier, & Meyer, 2010):

$$Stk = \frac{(\rho_P - \rho_L) u_{P,eff} d_P^2}{18 d_C \eta_L}, \tag{3}$$

where d_C is collector diameter. Low Stk values indicate that the particles can easily follow the flow stream lines that reduce the probability of collision with the collector. Based on the Stk, higher velocities will increase the significance of inertia on the probability of collision. This leads to remarkable bounce effects owing to the kinetic energy of the particles and stronger detachment forces F_d within the liquid (Hiller, 1981; Hiller & Löffler, 1980).

The probability of interception depends on the ratio of the particle size d_P to the interacting collector diameter d_C, and is termed the interception parameter N_I in Eq. (4). The higher the interception parameter, the higher the collision probability of a particle owing to its geometrical dimensions.

$$N_I = \frac{d_P}{d_C}. \tag{4}$$

Based on the work of Hiller and Löffler (1980), and Hiller (1981), this paper provides a simplified approach to determining the adhesion probability number, termed the Hiller number (Hi):

$$Hi = \frac{E_{adh}}{E_{K,1}} = \frac{\int F_{adh} dz}{(1/2) m_P u_{P,C}^2}, \tag{5}$$

where E_{adh} is adhesion energy between particle and collector, $E_{K,1}$ kinetic energy of particle before collision with collector, F_{adh} adhesion force between particle and collector, dz range of the interaction force between particle and collector, m_P mass of particle, and $u_{P,C}$ velocity of particle near the collector.

The Hiller number can be obtained from Eq. (5), which describes the relevant operating energies during collision of a particle with the filter structure. The higher the Hi, the higher the probability of adhesion of a particle to the filter. However, the equation neglects the effect of viscous displacement of the fluid film. Owing to the stiffness of the filter medium and particles, energy losses owing to plastic deformation are negligible. Besides the work of Hiller and Löffler (1980), the authors determined the adhesion energy between the particles and filter medium using atomic force microscopy (AFM), as introduced later.

$$F_d = \frac{\pi}{8} c_D \rho_L d_P^2 u_{L,eff}^2 \quad \text{with} \quad c_D = f(Re_P), \tag{6}$$

where F_d is detachment force acting on attached particle, c_D buoyancy coefficient based on Nirschl and Polzer (1996), Re_P Reynolds number of particle with a certain size, and $u_{L,eff}$ effective fluid velocity that acts on the attached particle. To describe the detaching force F_d exerted by the fluid flow on an attached particle, Eq. (6) was used. The calculation is based on the work of Nirschl and Polzer (1996),