Lorentz Force Particle Analyzer -Prototype experiments and numerical models

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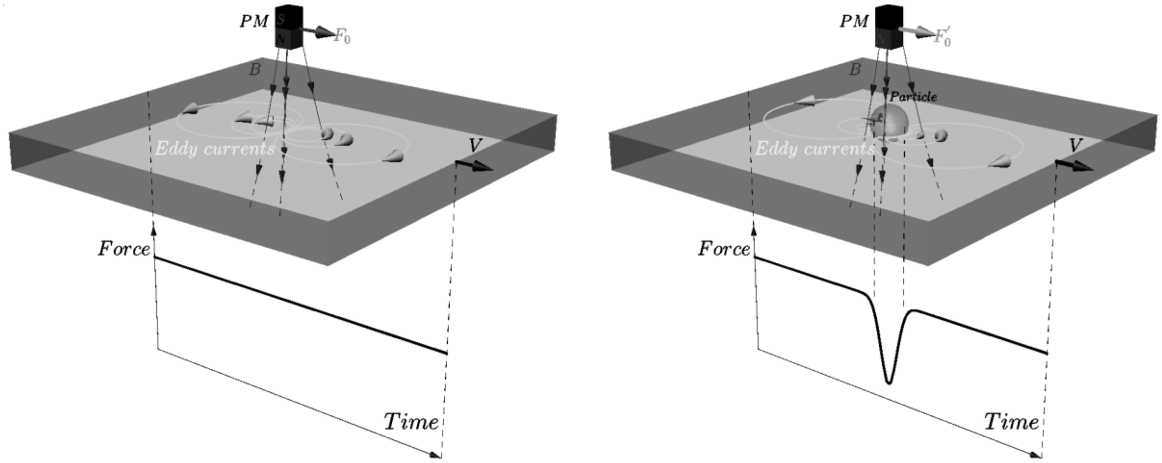
Abstract
A new contactless technique to detect micron-sized insulating particles in the flow of an electrically conducting fluid is presented. A transverse magnetic field brakes the flow and tends to be itself entrained in the flow direction by a Lorentz force, which can be measured. The presence of particles suspended into the fluid results in changes of this Lorentz force acting on the magnet, whose pulses allow to count and size the particles. This technique may be severed as a method for high-temperature metallic melt cleanliness inspection.

Key words:
Lorentz force, particles, permanent magnet, liquid metal cleanliness inspection

Introduction
In the 1940's, W. Coulter investigated suspensions of particles in a viscous fluid by forcing them to flow through a small aperture located in an insulating tube. Two electrodes were located on each side of the aperture and connected to an external source of electric current, so forming an electrical sensing zone (ESZ). When a particle is passing through the aperture, whose diameter is slightly larger than the particles, a voltage pulse signal can be measured and appears to be proportional to the particle size. The idea of this apparatus is itself known as the Coulter Principle (CP) [1, 2].
W. Coulter encountered considerable obstacles when he first tried to patent his idea. Arguing that "you can't patent a hole", several attorneys dismissed his invention. However, Coulter succeeded in 1953 and demonstrated that the aforementioned resistive pulse could be used to detect, sample and size particles in aqueous saline solutions, and this CP became the foundation of a growing industry in the domain of automated cell-counting instruments. Today, the CP is at the basis of more that 98% of the hematology measurements all over the world. Publications describing practical applications or theoretical designs now number in the thousands and related patents number in the hundreds. In 1997, when Beckman Instruments Inc. acquired Coulter Co., the Coulter brothers company had grown to 5,000 employees, with annual revenues of hundreds millions dollars [2].
Thirty years after the CP, McGill researchers made a breakthrough in the analysis of molten metal quality by applying the ESZ approach to this aggressive fluid. With this technique, now known as the liquid metal cleanliness analyzer (LiMCA) [3], the number of pulses can be related to the passage of insulating particles, although the amplitude of the measured voltage is millions of time smaller than that delivered for by saline aqueous solutions at with the same electric current. By using high amperages and high amplification rates, micro-voltages were successfully converted into clear signals above the background noise level. Since then, LiMCA has known a rapid development and been successfully used to monitor the quality of molten metals at still moderate temperatures, such as aluminum [4], zinc, lead solders, gallium, magnesium [5] and copper. However, it remains quite challenging to apply LiMCA to detect inclusions in melts like liquid steel, because of the high temperatures involved (1,600-1,700 °C) and material problems such as thermal shock, corrosion, melting, dissolution and blockage of the small orifice. In this paper, the Lorentz force particle analyzer (LFPA) is presented as a contactless method to overcome these challenges.
Lorentz force velocimetry (LFV) is another existing technique, which has inspired LFPA. A permanent magnet located in the vicinity of the liquid metal duct flow allows deriving the flow rate by measuring the drag force exerted on the magnet when the melt flows across the magnetic field [6, 7]. Because it is contactless, this technique can be applied to measure the flow rate of high temperature melts such as steels. However, so far, LFV has never been used for micron-scale measurements.
Inspired by CP [1] and LFV [6], here, we present an electromagnetic method for detecting and sizing particles suspended in the flow of an electrically conducting fluid.

Principle of the LFPA
Fig. 1 presents a schematic description of this method. When the particle-free melt moves across the magnetic field, as

shown on Fig. 1(a), eddy currents are induced in this electrically fluid and the associated Lorentz force brakes the flow. A reaction force is also exerted on the magnet itself, and can be measured with a high-resolution force sensor. Fig. 1(a) also indicates that this force (F_0) is constant in the case of a fluid flowing at a constant velocity. Fig. 1(b) shows, when an insulating particle is present within the electrically conducting melt, the difference conductivities results in a temporal and spatial redistribution of the eddy currents, which accordingly generates a significant change in the measured force (F'_0). The difference over time results in the formation of a negative pulse as seen also in Fig. 1(b). This suggests that the particle size can be derived from the functional dependence of on the particle size.



(a) (b)

Fig 1. Sketch of the Lorentz force particle analyzer (LFPA).
(a) Action of a small permanent magnet on the flow of an electrically conducting micro-scale fluid: a constant force F_0 aligned with the flow tends to brake the magnetic system; (b) the eddy currents are redistributed when a particle is present, which produces a negative force pulse.

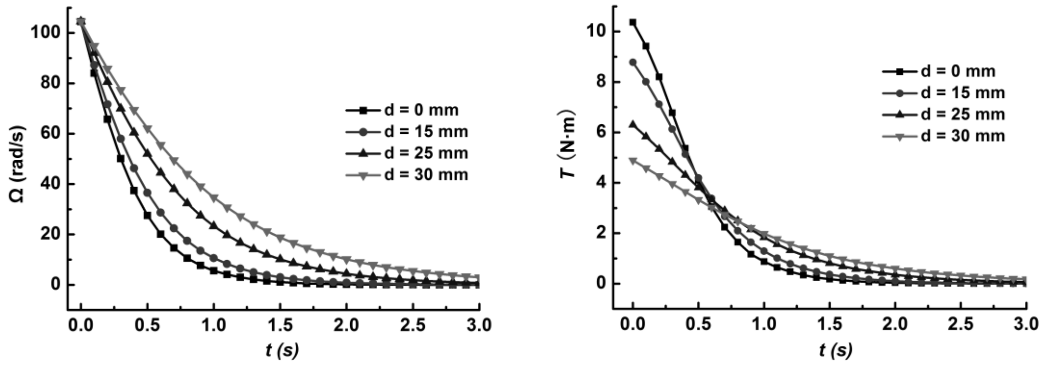
Prototype experiments and numerical models

In this prototype experiment, physically equivalent, we attempt to inspect mimicking defects via measuring the change of the electromagnetic torque. A single cylindrical permanent magnet, its magnetization direction is in one of its radial direction. Similar device has been investigated by J.Priede et al, but in his study, such device is used as an electromagnetic flow meter [8], while the present one is served as a prototype of particle analyzer.

A copper block is used to represent the electrical conductor being tested. Its dimensions are thickness 10 mm, width 50 mm and height 50 mm. A cylindrical through-hole of diameter *d* (=0, 15, 25 and 30 mm, respectively) is created perpendicular the widest surface of the conductor in order to mimic the insulating defect. When the permanent magnet rotates with an angular velocity (Ω), the eddy currents in the conductor are determined by Ohm's law $\boldsymbol{j}=\sigma(\boldsymbol{E}+\boldsymbol{v}\times\boldsymbol{B})$, where $\boldsymbol{j}$ represents the divergence-free eddy current in the conductor, $\boldsymbol{v}$ is the relative velocity of the conductor with respect to the magnetic field and $\boldsymbol{B}$ is the magnetic flux density. These eddy currents interact with the magnetic field to generate a Lorentz force acting upon the copper block, while a Lorentz reaction force acts upon the permanent magnet and tends to reduce its rotational speed by generating an electromagnetic torque [9,10].

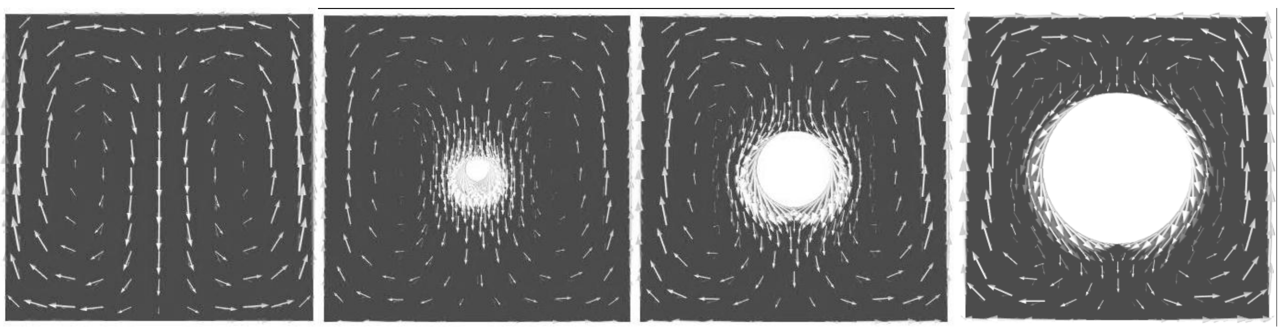
Typical curves of the angular velocity Ω and the torque $\boldsymbol{T}$ as functions of time t can thus be obtained. When an insulating defect (mimicking hole) is present in the copper block, the eddy currents are modified due to the difference in electrical conductivity between the defect and the conductor; the curves of Ω(t) (fig 2(a)) and T(t) (fig 2(b)) also exhibit differences, which can be related to the size of the defect. In our demonstration experiment, its diameter *d* can be determined from the variation in the attenuation curves.

This prototype reveals that the variation of either electromagnetic torque or Lorentz force can then be used as measuring parameter for detection insulating defects embedded in the conductor. In order to exhibit the underlying of such attenuation behaviors, we use a numerical model via a software package Comsol to simulate above experiment. As seen in fig. 3, the eddy current re-distribute as the hole-size increase because of the large difference in electrical conductivity between the conductor and the defect. Fig. 3(a) represents a copper block with no hole, for which the eddy currents in the centre vicinity is uniformly distributed. In fig. 3(b-d), the eddy-current distributions are different from that shown in figure 3(a). Clearly, the spatial distribution and magnitude of the eddy currents differ significantly for holes with different diameters [11].



(a) (b)

Fig 2. Prototypical model of a rotating cylindrical permanent magnet, magnetized in the radial direction with an initial angular velocity Ω_0=105 rad/s. The permanent magnet is placed near a copper block without or with a hole ((d=0, 15, 25 and 30 mm). Due to the Lorentz force, the motion of the copper block slows down the permanent magnet rotation; the evolution of the electromagnetic torque and angular velocity over time exhibits various attenuation behaviors depending on the hole-size.



(a) (b) (c) (d)

Fig 3. Eddy-current distributions for various values of *d* in cross mid-plane: (a) *d* =0 mm, (b) *d* =5 mm, (c) *d* =15 mm and (d) *d* =30 mm [11].

Another numerical model using the so-called numerical technique of moving meshes is built to demonstrate how the particle embedded in the electrical conductor to be detected. In order to adapt numerical technique of dynamic meshes, an electrically conducting wire in a ring shape is selected, when the length (perimeter when it bends as a circle) wire is long enough, the portion near the permanent magnet can be approximately considered as a straight. Here, in order to simplify the problem, two-dimensional model is adapted.

A permanent magnet sites closed to this ring wire with the gap of 0.5 mm, a non-conducting particle with a diameter of 200 µm is created in the wire; a static magnetic field is easily to be computed, the configuration and its magnetic lines is shown in Fig. 4(a). In this model, the ring wire and a portion of air exterior of it rotate in a certain velocity, the eddy current distribution with present of a particle at a certain moment is shown in Fig. 4(b). The Lorentz force density can be derived from the curl of eddy current and magnetic flux density as seen in Fig. 4(c). The reaction force acting on the permanent magnet finally formed a negative pulse, which clearly demonstrates the feasibility of LFPA as shown in Fig. 4(d).

Conclusions and perspectives

In this paper, we have been introduced the basic principle of LFPA, and exhibited its feasibility using the prototype experimental and numerical models. A key point in the LFPA is its capability to measure a small force, as shown in Fig. 4, let us estimate such capability, in order to detect particles of 200 µm in a metal whose electrical conductivity is of the order of 10^7 $S \cdot m^{-1}$, the force to be measured is about of the order of 10^{-3} N. Such a diagnostic appears rather straightforward with some kinds of the state-of-art force sensors. Since this force is proportional to the melt electrical conductivity, it is clear that the same technique should also work in semi-conducting materials whose conductivity is of the order of 10^6 S·m^{-1} as well.

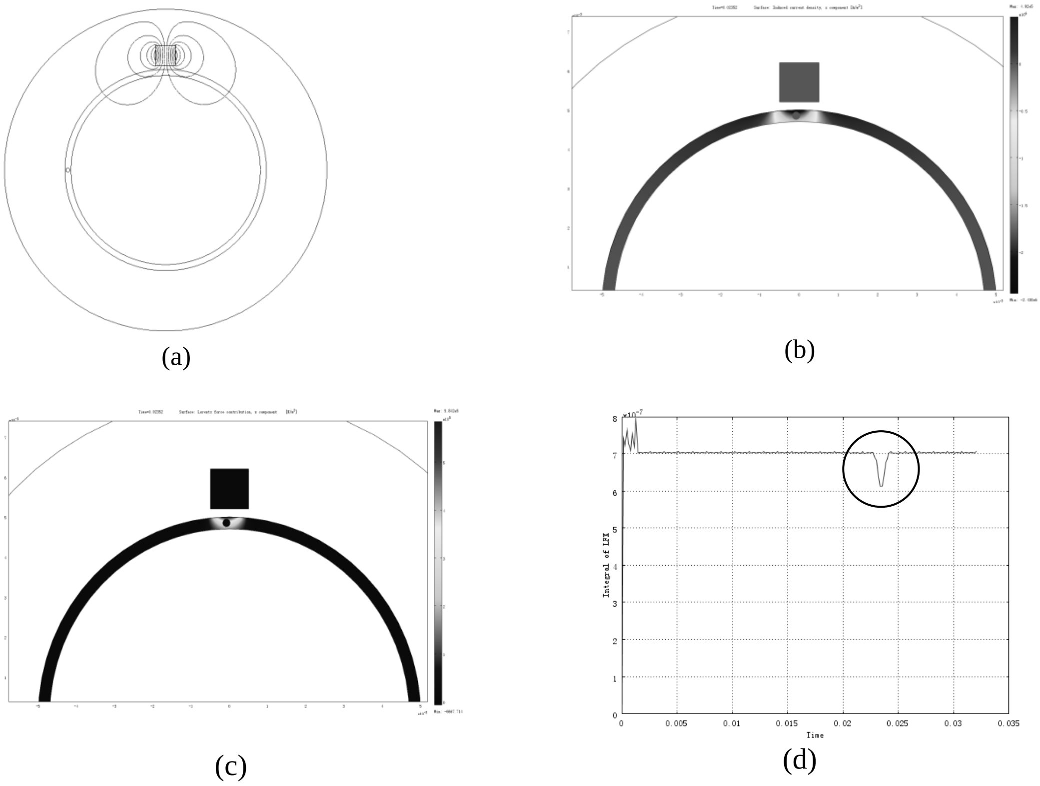


Fig 4. A Numerical model with moving meshes is built to investigate the main feathers of LFPA. The particle size is 50 um, and the diameter of the wire is 1mm, and consequently the order of the force can be of the order of 10^{-7}[N].

More technique information on the particles analyzer in industrial applications can be found in specific papers [12, 13]. It may conclude that such a LFPA, which has the merit of offering contactless and on-line measurements, could be applied to a wide range of applications, including the cleanliness of high-temperature and aggressive molten metals, such as aluminum and steel alloys, from which remove oxides like alumina or silica, as well as to clean semiconductors.

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References
[1] W.H. Coulter (1953), U.S. Patent No.2656508
[2] M. D. Graham (2003), J. Asso. for Labo. Auto. 12, 72
[3] D. Doutre, R. Guthrie (1985), U.S. Patent No.4555662
[4] R. Guthrie and M. Li (2000), Metall. Mater. Trans. B, 32B, 1067
[5] A.Thess, E.V.Votyakov, Y.Kolesnikov (2006), Phys.Rev.Lett. 96, 164501
[6] A.Thess, E.Votyakov, B Knaepen, O.Zikanov (2007), New J. Phys. 9, 299
[7] R. Moreau, Magnetohydrodynamics (1990), Kluwer Academic Publishers, Dordrecht
[8] J.Priede, D Buchenau, G Gerbeth (2009), Magnetohydrodynamics, 45, 451-458
[9] P. H. Roberts (1967), An Introduction to Magnetohydrodynamics, Elsevier, New York
[10] P. A. Davidson (2001), An Introduction to Magnetohydrodynamics, Cambridge University Press
[11] Y.Q. Tan, X.D.Wang, R.Moreau (2015), Meas. Sci.Tech. 26, 035602
[12] X.D.Wang, A. Thess, (2013), Germany patent pending
[13] X.D.Wang, A. Thess, T. Froehlich (2013), Germany patent pending