Trends of magnetic fluid applications in Japan

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Since the invention of magnetic fluid in the United States in 1965, the characteristics of the fluids have been progressively improved, and applications to various fields are growing. In this report the recent progress made in application devices of magnetic fluid will be reviewed focussing the techniques appraised as possessing, or promising the practical use in Japan.

1. Introduction

Though the beginning of magnetic fluid research in Japan was in the same time as the invention of magnetic fluid in the United States, the number of researchers related to magnetic fluid was relatively few until the 3rd International Conference in 1983. The 4th Conference held in Japan in 1986 collected wide concerns on the fluid. The increase of researchers since 1986 spread the recognition of the quality and standards of magnetic fluid and it reflected on the improvement of the fluids. Though big application was not necessarily realized for the last six years, applications to various fields seem to be certainly growing. In this paper the recent progress of magnetic fluid application is reviewed referring to the new attempts in research.

2. Applications

The first group of applications utilizes the property of a fluid that it is attracted and positioned by a magnetic field.

Seals

There are many kinds of seals ranging from miniature size (maximum transmitting torque 5 kg cm) to heavy duty size (6000 kg cm) in the market and applicable to each purpose. In seal applications, a strong magnetic field is formed around a shaft by arranging single or multiple permanent magnets and ferromagnetic pole pieces. The magnetic fluid is attracted to the gap as a liquid O-ring and opposes a pressure difference between both sides of the ring. One stage of magnetic fluid seal can practically support a pressure difference of about 0.2 kg/cm².

In vacuum seal, a multistage pole piece is used so that the total pressure difference amounts to 2 kg/cm² and 10⁻⁵–10⁻⁷ Pa is guaranteed by using a magnetic fluid of low vapor pressure. The merits of the seal are no leakage, long life (more than 10 years), and flexibility to the surface roughness of the shaft. The spreading application fields of magnetic fluid vacuum seals are crystal growing furnaces, ion plantators, X-ray tubes, electron microscopes, mass-spectrometers, vessels for spatter, CVD, ion and plasma etching, etc. [1,2].

Recently the need for a bigger shaft seal which can operate with high speed is growing in several projects. In the design of a flywheel system for electricity storage for example, the excess electricity in night time is reserved as rotational dynamic energy of a heavy rotor of a few hundred tons, and is used as electricity in day time. The rotor must be used in vacuum in order to reduce the pneumatic loss, and the development of a heavy duty, high speed shaft seal is required. For 10 MWh capacity for example, the rotor weighs 250 tons, maximum speed of revolution reaches 1862 rpm (peripheral velocity is 50 m/s for 120
mm diameter shaft), and an atmosphere of 0.01 Torr is needed [3]. Corresponding to these requirements, two approaches, that is, the design of the configuration of the seal gap and centrifugal type magnetic fluid seal are being attempted. Figure 1 shows the influence of the pole arrangements [4]. The seal with a ridge on the rotating shaft has an advantage over an ordinary type in the high speed region.

A single or double stage type is used as a dust exclusion seal for computer hard disks and robots in a clean room. In this usage, seals must be small enough so as not to affect the design of the hardware, and the thickness of the seal is reduced to 1 mm in practice. Further, a recent type of exclusion seal using electrically conductive magnetic fluid eliminates the leak system which is being used for leaking an electric charge built up on the computer hard disk [2] (fig. 2).

Inclinometer / accelerometer

Two types of inclinometer or accelerometer have been reported. One utilizes the self buoyancy of a permanent magnet. The change of acceleration is detected by sensing the displacement of the magnet floating in a magnetic fluid. Figure 3 shows the tilt switch adopting this mechanism [5]. A permanent magnet is kept floating at the center of the container, and the lead switch works by the decrease of the magnetic field when the container inclines. Cobalt metal magnetic fluid is used in this sensor for obtaining high response. Another type detects the change of the thickness of the magnetic fluid adhered to a permanent magnet by an induction coil, when the magnet feels the change of acceleration. This type is not so sensitive but operates stably and restores the form of the magnetic fluid after a strong shock. The former type replaces the level instrument used in surveying and the latter seems
to be studied for detecting severe shock, such as an earthquake or an automobile accident.

Printers

Though the application of a magnetic fluid to printing systems is not commercialized yet, much interest is concentrated to this field because of its future market size. A feature of a magnetic fluid is that it can provide a stable ink feed system by using a magnetic field. Multi-stylus type magneto-fluid-graphy was demonstrated as a practical printer [6]. The structure and performance of this printer is detailed in the Proceedings of the 3rd Conference on Magnetic Fluids. This basically utilizes the effect that a magnetic fluid migrates along a magnetized guide (multiple extrusions) to reach the potential equilibrium.

The magnetic fluid ink on the top of the extrusion flies toward the counter electrode through Coulomb force by an electric field with the recording paper in between. The high performance of 248,000 dots/s and 8 dots/mm is demonstrated in this machine.

In a copying machine called ‘magnetography’, the magnetic pattern on the drum is developed with magnetic toner and transmitted on the paper [7]. Figure 4 shows the principle. The magnetic pattern is written in the same manner as that in audio or video recording. The prevailing printer has realized a density of 17.9 dots/mm and a printing speed of 100 sheets/min with a dry developing method. The big advantage of this system is that it can produce a large number of prints, practically about 1000 sheets, with one magnetic record. It is said that the resolution in this printing is restricted by the adhering behavior of the magnetic toner (10−15 μm). In order to improve the resolution of the picture, a toner with smaller size and higher dispersability is desired. Magnetic fluid, for its high dispersion stability and small particle size, may have the possibility of finding application in this area.

In any case, a serious problem of magnetic fluid ink will be the color of the fluid. The preparation of colored magnetic fluid is thus being
studied. The colored magnetic fluids reported at present are prepared by adding dye to the magnetic fluid containing Mg-Zn or Mn-Zn ferrite [8]. We have to select a dye and a magnetic colloid taking the dispersion stability and color interference between them into consideration. Magnetic fluids using colored magnetic particles may be desired in the future. The magnetic viewer, which visualizes the magnetically recorded pattern on magnetic tape or disk, has widely prevailed and its reliability is well known.

The second group of applications utilizes the magnetically induced levitation force on magnetic or nonmagnetic bodies.

**Bearing**

A new type of hydrodynamic bearing is developed by introducing a magnetic fluid held by a permanent magnet [9]. With the increase of magnetic or optical recording density, more precise performance has been required of the spindles in audio, video and computer systems. This fluid bearing is composed of a shaft with a Rayleigh step which produces radial hydrodynamic pressure, and two thrust bearings which support the shaft between them. Magnetic fluid is used as the working fluid and is kept in the bearing by magnets on both sides. The non-repeatable run-out of traditional precise bearing (~ 0.1 μm) is drastically decreased with this bearing. This eliminates accessory devices needed in aeropneumatic pressure bearing and its size is similar to that of a usual bearing.

**Magnetograinimetric separation**

A sink and float separation plant for treating metal scraps has been developed using a water based magnetic fluid and a rare-earth permanent magnet. This system reduced major expense of electricity and the water based magnetic fluid has advantages in cost, ease of treatment and efficiency of recovery from smeared products after the treatment. Figure 5 shows the structure of the density separator [10]. The line of maximum gradient of the magnetic field is slightly inclined from vertical, and the magnetic levitation force on the non-magnetic bodies has a horizontal component (left-hand in the figure). The floating light materials spontaneously move to the left beyond the magnet and are collected by a conveyor. This separator precisely treats Al, Zn, Cu, Pb and related alloys smaller than 30 mm in diameter.

**Damper**

A magnetic fluid offers an expelling force to a nonmagnetic body in a magnetic field gradient and hence enables it to be positioned with the aid of a magnetic field. Also, a permanent magnet itself floats spontaneously in the magnetic fluid. These characteristics enable the application of magnetic fluids to various viscous dampers. In the application to a moving coil loudspeaker, a magnetic fluid fills the space of the magnetic gap and stabilizes the movement of the coil. The heat arising from eddy currents in the coil is transferred by the thermoconvection described in the latter part, and the maximum power of the speaker increases by about 50%. Other applications to control unwanted oscillations of functional parts of instruments cover printers, x-y plotters, gauges, floppy disk head positioners [1], loading table of vibration isolators [11], and so on.
Grinding and polishing

The requirement for precise grinding is increasing in many fields of technology. Correspondingly, a new surface finishing method combining a magnetic fluid and abrasive grains under a controlled magnetic field is a developing new field among traditional mechanical technology. The buoyant force to nonmagnetic bodies in a magnetic fluid is applied in this method. Figure 6 shows the principles of grinding ceramics as plane, sphere and roller [12-14]. The abrasive grains of a few to a few hundred micron in size are suspended in a magnetic fluid of water or oil carrier, and a workpiece is slid on a pad, floating in the fluid. The magnetic buoyant force plays two important roles in this process. One is to make the abrasive grains float so that the grains are continuously fed to the polishing section. Another is to give the compressive force between the floating pad and the workpiece so that the removal rate in grinding can be controlled. There is no crushing of the abrasive grains at the surface of the workpiece in this process, because the direct support of the abrasive grains by the base ground is eliminated by introducing magnetic levitation force. It is proven that a silicon nitride sphere with a practical use grade is obtained with a forty times higher grinding rate compared to the traditional method. In flat plane finishing, an aluminium plate with a minimum flatness of 0.5 μm is obtained with a maximum removal rate of $7 \times 10^{-12}$ m$^3$/Nm.

The third group of application is heat transfer devices. The main factors distinctive to the magnetic fluids will be the thermomagnetic convection and the magnetic buoyant force to the bubble formed by boiling.

Magnetocalorimetric pump

A magnetocalorimetric pump system with magnetic fluids is considered to have application fields in heat transfer such as solar systems, snow melting, cooling of mechanical or electric heat sources. In order to improve the driving force of this system, improvement of the magnetic characteristics of the colloids or a supplemental system such as injection of air bubbles is being investigated (fig. 7) [15,16]. Concerning the introduction of air bubbles, adding to the usual gas injection, steam injection, or boiling by means of a heater inserted in the loop is investigated. When steam is injected, the temperature sensitive magnetic fluid whose magnitude of magnetization strongly depends on the temperature, provides a high pressure difference due to the reduction of magnetization by both the air mixing and the temperature effect.

It is also possible to control the distribution of heat flux in a magnetic fluid pool by a magnetic
The promotion of cooling in a loudspeaker damped with a magnetic fluid has been pointed out from early days. Heat design taking thermomagnetic convection into consideration will further improve the power of a loudspeaker. The cooling of other local heat sources such as semiconductors is being studied.

Among the subjects of heat and mass transfer in magnetic fluid, interests seem to be grouped into three fields as follows [17]: (1) the promotion or control of heat transfer between heating wall and magnetic fluid; (2) the control of thermal convection; (3) the promotion of heat transfer associated with nucleate boiling. The number of experimental reports is not very high yet. The transfer of heat from a platinum wire into a temperature sensitive magnetic fluid is enhanced by applying a magnetic field under no forced convection [18]. On the other hand thermovective phenomena in a magnetic fluid have been studied mainly from theoretical viewpoint. The reference of theoretical predictions to practical behavior is being performed with the aid of visualization techniques, for example using a liquid crystal sheet or infrared thermography [19]. Now the research of nucleate boiling of a magnetic fluid is still at its start, and three features are observed as follows: (a) Heat transfer is enhanced independent of a magnetic field by the presence of ferrite colloids of low concentration. (b) Heat transfer is promoted by the application of a magnetic field in the magnetic fluid of moderate concentration, and suddenly transits to a superheated state at a higher heat flux region. (c) The heat transfer is strongly depressed in a magnetic fluid of high concentration.

**Heat pipe**

The performance of a magnetic fluid heat pipe is studied as a case of heat transfer accompanied with boiling [20]. The working fluid in a heat pipe of siphon type is replaced with a magnetic fluid, and a magnetic field is applied at the bottom of heating section. Figures 8 and 9 shows the heat pipe arrangement, and heat transfer characteristics as a function of the strength of the magnetic field.
The fluid is magnetite based hexane with a concentration of 36.1 wt%. It is known that a heat pipe works more precisely at constant temperature by applying a magnetic field than a heat pipe using hexane. The bubbles formed by boiling are quickly removed from the fluid pool, resulting in an increase of latent heat transfer and it is confirmed that the maximum capacity of heat transfer at moderate concentrations exceeds that of a pipe using a pure carrier liquid of magnetic fluid.

3. Summary

The trends of magnetic fluid applications and some topics on the way of research are reviewed. Out of these, there are reports on fundamental studies of the constituents of an actuator such as the movement of a magnetic fluid plug or the flow of a magnetic fluid under a moving magnetic field, a vermicular pump using a magnetic fluid, or characteristics of optical switches.

In many cases application oriented studies meet the barrier limiting the magnetization of magnetic fluids. The development of strongly magnetizable fluids is expected to be a break through in this respect. It must be noticed from this viewpoint that a new magnetic fluid (Fe₃N in inorganic solvent) with saturation of 2700 gauss has been realized by an original process. Ultrafine (6 nm) Fe₃N particles are prepared in kerosene by the reaction of iron carbonil, ammonium gas and amines in this process. The specific initial magnetic susceptibility of this fluid reaches 180, which is the highest record of powder magnetic materials exceeding those of Sendust or permalloys. The mechanism of the magnetization in this fluid waits research after this, and it will promote new applications.

References


