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CONTROLLABLE FLUIDS – MATERIALS WITH THE ABILITY TO CHANGING THEIR PHYSICAL PROPERTIES

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Abstract

Controllable fluids (smart liquids) are the substances that change their properties under the influence of external physical fields. Changes of these liquids properties take place in a controlled manner and they are fully reversible. The ability to changing nature of work is a very important aspect that determines their vast application possibilities. It also makes they are occupying significant place in the modern engineering.

Content of this report has been in turn devoted to systematization information on the properties and work of magnetically activated controllable fluids. There have been highlighted some commonalities and differences between two basic types of magnetic fluids (ferro- and magnetorheological fluids). Essential areas of controllable fluids application and their production methods have also been presented within this notice.

It seems to be more than reasonable to explore this title issue using new methods of research and observations. They in fact directly create another chances for discovery unknown features or simply adapting the existing ones to current technical expectations. What are also important, smart liquids can be threaten as highly advanced materials which synthesis cover manipulation on the already known substances and do not cause any environmental pollution. Discovered over sixty years ago, they still signalize a great potential to development.

Keywords: *controllable fluids, smart liquids, magnetorheological fluids (MRF), ferrofluids (FF)*

1. Introduction

The dynamic progress within many scientific disciplines, particularly over the last a few decades, had direct influence on technological advancement in the field of controllable fluids (smart liquids). Successive examples of the implemented industrial applications that use controllable fluids directly or which are supported by them indirectly; they lead to the conclusion that these specific fluids are occupying an important place in the modern engineering field. Simultaneously they are demonstrating the great potential to development of some further innovative designs or respectively to performance increasing within the already existing designs.

Considering this what above, it appears understandable to scrutinize this title issue throughout some new methods of monitoring and detailed investigations. The main aim of this study is assumed rather to systematize information on the operating characteristics, main properties and the behaviour of controllable fluids. There are also some possible subjects for consideration proposed.

2. Controllable fluids

The term "controllable fluids" is in fact quite new and it is commonly used just for several last years. In general engineering practice, it is usually understood as a broad name of the substances that change their properties under the influence of external physical fields. Genesis that concern directly composition of these substances for the first time, it reaches the first half of the twentieth century. Their development was initiated by W. Winslow [18], who has produced electrorheological fluid (ER) changing its mechanical properties (viscosity, yield stress) as a result of electrostatic field impact and J. Rabinow [15] – the discoverer of magnetorheological fluid (MRF) changing its properties due to magnetic field changes [1, 2].

Differentiation among steerable fluids types requires introduction of some proper classification, distinction specific subgroups and using the correct nomenclature. Properties description of all controllable liquids strongly exceeds the volume of a single article, so in this study the notice will be focused on magnetically activated fluids (MRF – magnetorheological fluids), among which we can distinguish magnetorheological fluids (MR) and ferromagnetic fluids (FF). Issue of the other controllable fluids types will be continued within next papers.

3. Magnetically activated fluids

The basis for MRF fluids functionality is closely related to their presence in the area of magnetic field lines influence. For the case when MRF liquid is out of magnetic field, its properties and behaviour are (in a simplification) approximated to the Newtonian fluid – shear stresses present in the liquid volume are proportional (1) to the speed of deformation [2, 3]:

$$\tau = \mu\dot{\gamma}\,,\ B = 0, \tag{1}$$

where:
τ – shear stresses in a liquid [Pa],
μ – dynamic viscosity of the liquid [Pa*s],
$\dot{\gamma}$ – shear strain rate [s^{-1}],
B – outer magnetic field strength [A/m].

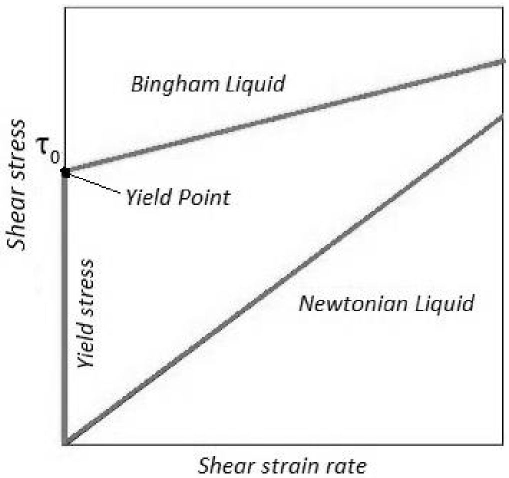

Fig. 1. Shear stress to shear strain rate dependence for Bingham and Newtonian liquid models

Significant changes in behaviour and properties occur when the fluids are under influence of magnetic field – they correspond to the Bingham fluid model (Fig. 1). Symptomatic property of behaviour and functioning in such a state is the limiting shear stress (τ_0) occurrence. Below τ_0 value, controllable liquid character corresponds to elastic solids. When the τ_0 crossed, it takes on characteristics appropriate to Newtonian fluid, for which dependence (2) is fulfilled:

$$\tau = \tau_0(B) = \mu\dot{\gamma},\ \ B > 0, \tag{2}$$

where τ_0 – boundary yield stress point in controllable liquid [Pa].

MRF fluid structure is usually composed of three basic components: a liquid fraction carrier, solid ferromagnetic particles and protective substance (so-called surfactant). Dispersion liquid is a basis and a carrier for the deployment of ferromagnetic particles. Depending on the application, as the carrier liquid there can be used oil (mineral, synthetic or silicone-based), glycerol, derivatives of fluorinated hydrocarbons, esters, diesters or even water. It has to be magnetically neutral liquid that meets requirements for density, viscosity and evaporate [19]. Ferromagnetic particles are obtained by mechanical grinding, milling (usually oxides of iron, cobalt and magnetites) or chemical synthesis [1, 4]. The surfactant itself is in turn formed by accompaniments of surface-active substances such as higher fatty acids. They are producing thin protective layers around ferromagnetic particles that suppresses acting of the intermolecular *Van der Waals* forces and do not allow to undue closing, linking into colonies and in consequence gravitational sedimentation (Fig. 2). In practice, there are commonly observed cases in which certain anti-corrosion agents are added to the MRF liquids. The main goal for this is to obtain some specific properties and operating conditions.

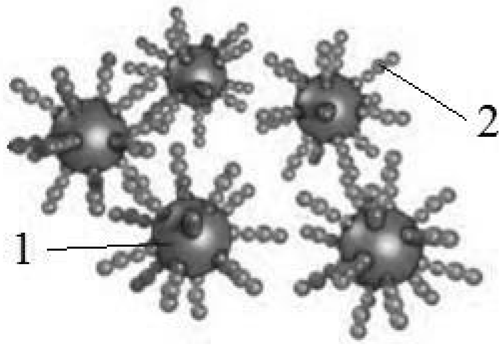

Fig. 2. Surfactant molecules chains (2) that prevent ferromagnetic particles (1) against their aggregation [21]

Controllable fluids may also be obtained using chemical methods in so-called chemical polycondensation process. It involves mixing of two solutions having different valencies. In result, a suspension of fine ferromagnetic particles is obtained. This is faster and more economical method in comparison to mechanical ferromagnetic milling. According to [10], thanks to chemical synthesis it is possible to control particles shape and size what in fact creates possibility for obtaining high quality and high homogeneity liquid.

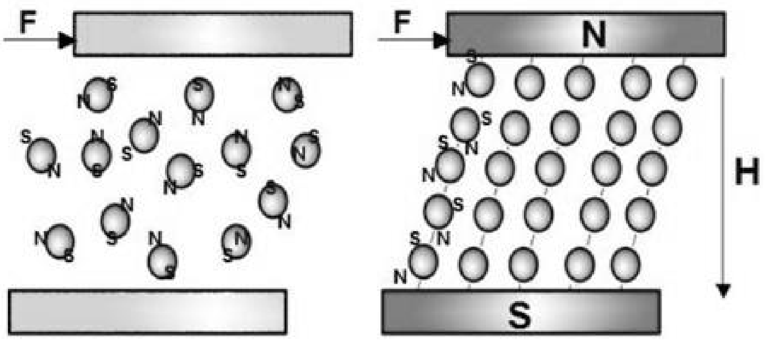

Fig. 3. MRF liquid particles in a non-active state (on left) and under magnetic field influence (on right) [1] (Explanations: F – external loading that moves one of two opposite magnet poles, H – magnetic field vector)

Looking through the prism of industrial MRF fluids applications, the most interesting thing is the ability to change their physical properties through magnetic field forces acting. The consequence is a regular orientation of molecules so far freely floating within the carrier volume. Ferromagnetic particles are set up according to magnetic field lines what makes them to create ordered chains structures (Fig. 3 and 4). These formed structures cause an increase in viscosity, shear stress values and appearance of the apparent yield stress (only in MR fluid case) [16]. The higher magnetic field strength and induction, the more tension among these formed ferromagnetic chains and the greater viscosity of the liquid. That is why MRF liquids can serve vibration damping and absorption of energy from the shock. They can also stimulate actuators movements within systems that use controllable liquids to create acting forces.

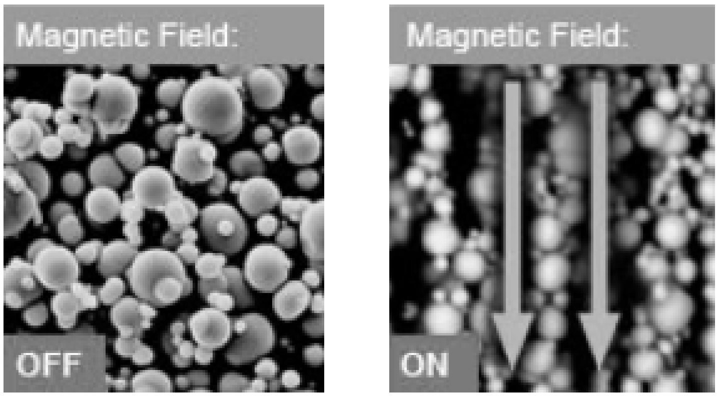

Fig. 4. MRF liquid in a non-active state (on left) and regular MRF liquid particles chains in magnetic field (on right). Scanning electron microscope photos [23]

Change in viscosity under magnetic field forces is the common feature for all MRF fluids. Their stiffening phenomena is fully reversible when field forces terminated – particles concentrated in chain structures are dispersed, liquid recovers the Newtonian fluid character so its internal friction becomes much more smaller. Period of the time, over which controllable liquid returns to its original state due to lack of field forces, it usually varies between a few to a several milliseconds what is fully satisfactory in terms of technical applications. Interest among scientists and comprehensive consideration of the various aspects that accompany to controllable fluids work, they all ultimately led to distinguishing two subgroups of MRF liquids [1, 11, 12]:

- Micro-magnetorheological fluids MR (magnetorheological fluids), for which ferromagnetic particles are at the size of a few micrometres,
- Ferrofluids FF (nano-magnetorheological fluids), for which ferromagnetic particles sizes vary from a few to ten nanometres.

In practise, there exist both numerous commonalities and some distinctive properties in between these distinguished MRF fluids types. Thus, for example, FF fluids unlike to MR fluids, they do not present a yield point. They are characterized by roughly ten times less value of the maximum shear stress (usually not exceeding 5kPa) and greater resistance to sedimentation phenomenon – this is associated with much smaller sizes of ferromagnetic particles, less liable to gravitational fall. Moreover, ferrofluids exhibit high magnetic stability and the ability to work in a wide range of temperature (-60 up to 200°C). Tendency of FF liquid to changing its parameters through composition modification (viscosity variation in range from 5 up to 25 000cP) as well as mastering the detailed knowledge about technology of their production make that some new applications can be regularly observed.

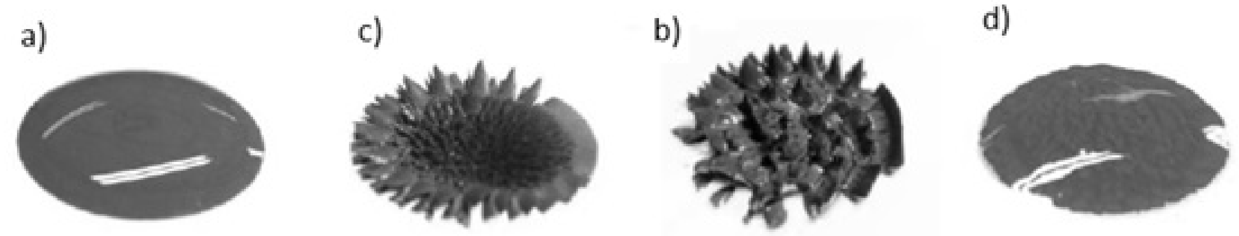

Fig. 5. A drop of magnetorheological liquid MRF-122EG type: a) liquid without magnetic field; b), c)liquid under the operating magnetic field (different distances to the source); d) liquid after removal of the field [14]

Among plural applications, the most recognized are sealing for both static and moving mechanical connections (Fig. 6), vibrations damping (Fig. 7), supporting thermal conductivity and heat exchange but also noise reduction in electromechanical devices.

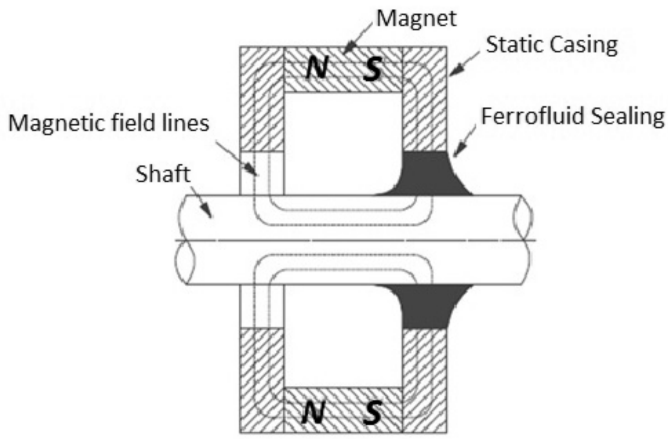

Fig. 6. Ferromagnetic seal of the movable connection shaft to its casing support [9]

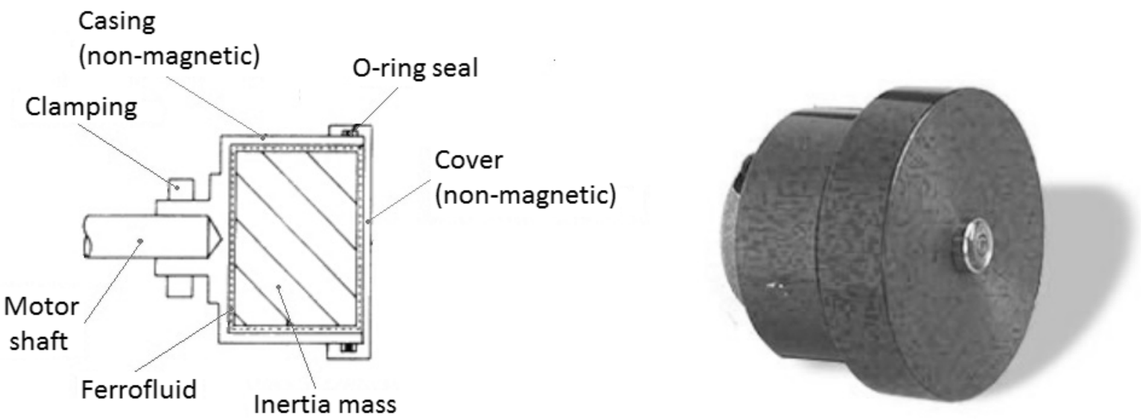

Fig. 7. Ferromagnetic fluid based oscillation damper used in step motors [22]

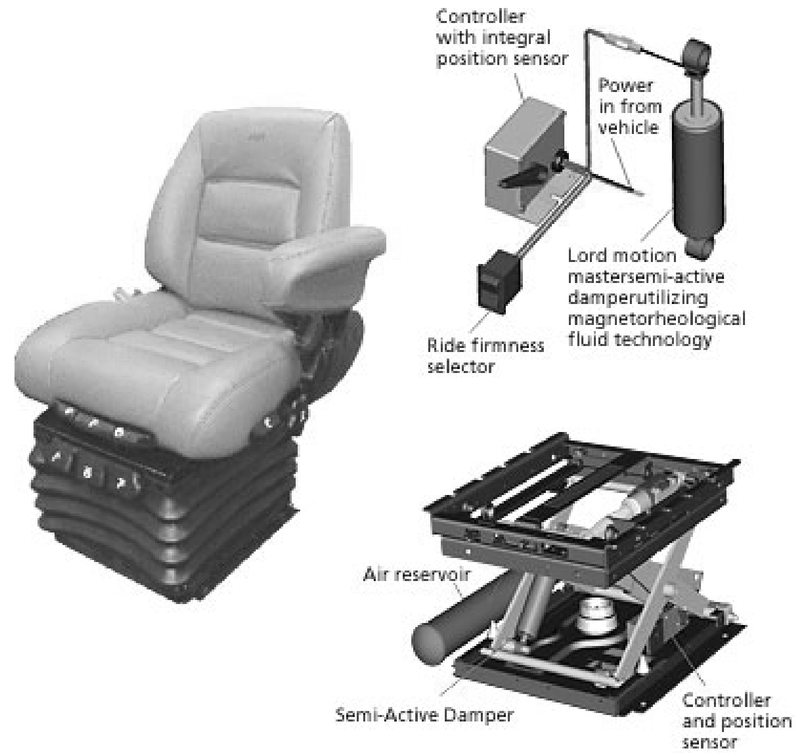

Fig. 8. Driver's seat with the vibration damping system based on MR fluid [24]

As stated within numerous scientific notes (e.g. [5, 8, 12]) and based on information provided by manufacturers, ferromagnetic particles, volume content in FF liquids is usually between 3-15%. Practically implemented FF fluids contain 85% of the carrier liquid, 5% of the ferromagnetic particles whereas 10% is dedicated to protective surfactant coating. In contrary to FF fluids, MR fluids are characterized by a higher share of ferromagnetic particles that stays between 20% and 80%. This amount of solid ferro-particles significantly influences the magnetization saturation. MR fluid preserves its properties at a slightly smaller temperature range compared to FF liquids (approx. -50 to 150°C). What is interesting, even at a small magnetic field there can be observed a significant change in viscosity. All of that is caused by a considerable share of the ferro-particles. From practical point of view, the biggest MR fluid advantage over FF fluid stays the relatively low production cost. It makes the substance can be easily and widely used within engineering technology. To stay fair, it has to be said that the biggest observed disadvantage of the MR fluid is its liability to gravitational sedimentation, which in fact can significantly affect some work characteristics [14].

Dependency between magnetization and intensity of the magnetic field for selected MR and FF fluids types has been presented within Fig. 9. From the plot, we can conclude that both considered MRF fluids are almost perfect soft magnetic materials. Additionally, for some fixed magnetic field value both MR fluids exhibit several times higher magnetization than the FF liquid.

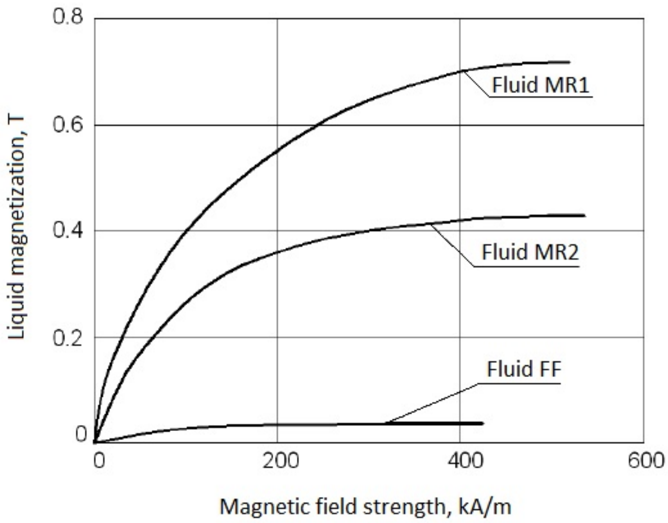

Fig. 9. Magnetization curves for some types of ferro- and magnetorheological fluids ([6], [14]). Explanation: Fluid MR1: iron particles size 4.0-5.3 µm, 35% of the volume, Fluid MR2: iron particles size 10 nm, 35% of the volume, Fluid FF: iron particles size 10 nm, 10% of the volume

The considered physicochemical properties and liquid form determine strong controllable fluids suitability for engineering applications. However, to satisfy all expectations properly, it is necessary to maintain the controllable liquids in a good condition. Thus, there should be possibly uniform fluid consistency and proper ferromagnetic particles surface structure maintained.

4. Summary

A great progress and numerous achievements within MRF liquids subject have been gained over the past decades. However, literature analysis points on some constant basic research and technology problems [7, 13, 17, 20] that still stay unsolved. Most likely, they will constitute direction for future research activities. For deeper analysis surely remain problems of precise MRF fluids behaviour control, mathematical description of the liquids states' changes phenomena but also steerable liquids implementation within newly created designs.

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