Thermomagnetic convection influenced by the magnetoviscous effect

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Abstract. The mechanism of thermomagnetic convection in ferrofluids which is introduced by a magnetic field is well understood. To describe this kind of convection, it is assumed that the material properties, e.g. the viscosity $\eta$ are independent from the magnetic field. However under certain circumstances ferrofluids show a magnetoviscous effect that means the increase of $\eta$ in the presence of a magnetic field. Both effects have been well investigated but independently from each other. In this paper it is experimentally shown how the magnetoviscous effect and therefore the increase of $\eta$ influence the behaviour of the thermomagnetic convection.

1. Introduction
Under certain circumstances thermomagnetic convection arises in a horizontal ferrofluid layer if an external magnetic field is applied and additionally a temperature difference over the fluid gap exists [1, 2]. This situation causes a magnetic body force in the ferrofluid layer which can drive a convective flow [3]. The density of this magnetic force is given by $f_m = \mu_0 \cdot M \cdot \nabla$. The characteristic of thermomagnetic convection can be described by the dimensionless magnetic Rayleigh number $Ra_m$ which is given by

$$ Ra_m = \frac{\mu_0 \cdot \partial M / \partial T}{\kappa \cdot \Delta \eta} \cdot \nabla \cdot \Delta T \cdot d^3 $$

$$ = \frac{\mu_0 \cdot |H| \cdot \Delta T \cdot d^2}{\kappa \cdot \Delta \eta} $$

where $\nabla H$ and $\Delta T$ denote the inner magnetic field gradient and temperature difference over the fluid gap with thickness $d$, $\mu_0$ is the vacuum permeability, $K = \partial M / \partial T$ is the pyromagnetic coefficient, and $\kappa$ and $\eta$ the temperature conductivity and the dynamic viscosity of the fluid respectively. The critical Rayleigh number $Ra_{m,\text{crit}}$ for a horizontal fluid layer which is covered by two rigid boundary plates is 1708 [2]. Below this value the heat is transported by a diffusive process and changes to convective state if $Ra_{m,\text{crit}}$ is exceeded. For this case where the convection is described by $Ra_m$ it is assumed that the material properties of the ferrofluid are independent from the applied magnetic field with the exception of the inner magnetic field $\nabla H$ and $K$ obviously.

A second well known phenomenon appearing in ferrofluids is the magnetoviscous effect [4 - 7] which describes the change of viscosity $\eta$ under the influence of an applied magnetic field. In many high concentrated ferrofluids a contingent of large particles exists with a magnetic interparticle interaction...
strong enough to form chainlike structures. This particle formation leads to an increase of $\eta$ which depends on the magnetic field strength and shear rate. To determine the magnitude of the magnetoviscous effect, an interaction parameter $\lambda$ has to be introduced defined as the ratio between magnetic interaction energy between two particles which are in contact and their thermal energy. Nevertheless the direct contact of two particles is usually avoided by a surfactant to fight Van der Waalz forces. These forces will otherwise cause agglomeration of the particles leading to sedimentation which destroys the magnetic fluids. The influence of the surfactant layer is considered by a modified interaction parameter $\lambda^*$ which is given by

$$\lambda^* = \lambda \cdot \left(\frac{d}{d + 2 \cdot s}\right)^3 = \frac{\mu_0 \cdot M_0^3 \cdot V}{24 \cdot k_B \cdot T} \cdot \left(\frac{d}{d + 2 \cdot s}\right)^3$$

where $\mu_0$ denotes the vacuum permeability, $M_0$ the spontaneous magnetization of the magnetic material, $V$ the volume of the magnetic particle, $k_B$ the Boltzmann constant, $T$ the absolute temperature, $d$ the mean diameter of the particles and $s$ the thickness of the surfactant. If the value of $\lambda^*$ is larger than 1 the interparticle interactions are strong enough to build chainlike structures which can affect $\eta$. For magnetite particles, chain formation becomes effective for $d \geq 16$ nm.

In this paper it is described how the magnetoviscous effect influences the thermomagnetic convection in ferrofluids. Both phenomena have separately been well investigated in the past but the possibility of a concurrent appearance has never been considered.

2. Experimental data

2.1 Ferrofluid samples

For the investigation of the above described effects, two samples of a commercial ferrofluid called APG 513A from Ferrotec, Germany, are used. The samples, which have in principle the same fluid and magnetic properties, differ in their microstructure. The sample APG 513A_OLD which was produced by a former production process has a broad particle size distribution which means that it contains large particles which are able to force the magnetoviscous effect. The second sample APG 513A_NEW, which was produced by a modern production process, has a small particle size distribution, so that most of the particles have a diameter close to the mean diameter which is 10 nm.

The ferrofluid consists of magnetic particles made from magnetite (7,2 vol. %) suspended in synthetic ester. The saturation magnetization $M_S$ is 28,2 kA/m at room temperature of 20 °C and the pyromagnetic coefficient $K$ is 35,3 Am$^{-1}$K$^{-1}$ for a field strength of 25 kA/m. Further basic fluid properties are the thermal expansion coefficient $\beta_T = 4,5 \times 10^{-4}$ 1/K, the temperature conductivity $\kappa = 5 \times 10^{7}$ m$^2$/s and the viscosity $\eta_{(T = 20 \degree C)} = 170$ mPas.

2.1. Magnetoviscous effect

The change of $\eta$ under the influence of an applied magnetic field was investigated with the shear-controlled rheometer described in [8] with some technical modifications. The magnetic field is generated by a pair of Helmholtz coils with a maximum field strength up to 40 kA/m and the field homogeneity in the center of the coils is better than 95 %. The measurement cell of the rheometer consists of a cone-plate geometry and allows shear rate variations in the range from $10^1$s$^{-1}$ to $10^3$s$^{-1}$. Figure 1 shows the change of viscosity $\Delta \eta$ as a function of the applied magnetic field strength for a shear rate of 0,1 s$^{-1}$. For the sample APG 513A_NEW only a very weak increase of $\Delta \eta$ can be seen. This change reaches 50 % of the viscosity $\eta$ at $H = 0$ kA/m for a field strength of 30 kA/m. The increase of $\Delta \eta$ changes dramatically for the sample APG 513A_OLD. Here a change of viscosity by a factor of 4,4 for a field strength of 30 kA/m can be found. This sample has a contingent of large particles which give rise to a strong viscosity change.
Actually a small amount of the particles in this sample - volume concentration \( \Phi = 0.8\% \) - have a mean diameter of 16 nm, leading to a magnetic interparticle interaction parameter \( \lambda^* = 2.87 \) [9].

2.2. Thermomagnetic convection

The behaviour of thermomagnetic convection under the influence of a magnetic field was investigated with a specialized measuring cell [10] which is modified with a heat flux sensor. The setup provides the possibility to measure the temperature difference \( \Delta T \) and the heat flux \( Q \) over a horizontal fluid gap with a height of 4 mm and a diameter of 88 mm. The magnetic field - maximum possible field strength is 25 kA/m - is generated by two pairs of Helmholtz coils placed in a Fanselau arrangement. The inhomogeneities in the center of the arrangement are smaller than 0.5%. The temperature is measured by thermistors with an accuracy of 0.01 K. Furthermore the heat flux sensor has a accuracy of 0.1 W/m\(^2\). The temperature difference over the fluid gap is generated by two water chambers above and below the measuring cell with a temperature stability of 0.01 K.

In figure 2 the behaviour of \( Q \) as a function of \( \Delta T \) for a horizontal fluid layer heated from below is shown for the sample APG 513A_NEW. Without an applied magnetic field only the thermal convection which is driven by the bouyancy force works. The characteristic of the heat flux transfer changes from a diffusive state to a convective state where the slope of \( Q \) changes remarkably. At this point the critical Rayleigh number of 1708 and therefore the critical temperature difference \( \Delta T_{\text{crit}} \) of 32 °C are reached. With an applied magnetic field the situation changes because two mechanisms - thermal and thermomagnetic convection - are working simultaneously. The heat flux \( Q \) increases in general because of the additional heat flux introduced by the magnetic force. Due to this additional heat flux the critical Rayleigh number is reached for a value of \( \Delta T_{\text{crit}} \) which is smaller by a factor of 2 than the value of \( \Delta T_{\text{crit}} \) for \( H = 0 \) kA/m. For this sample it is assumed that the material properties of the ferrofluid sample, e.g. \( \mu_0 \), \( \kappa \) and \( \eta \), are independent from the magnetic field. Further it can be seen that for a magnetic field of 25 kA/m the slope of \( Q \) does not change abruptly at the transition point, but rather a transition zone exists. This behaviour is caused by the characteristic of the microstructure of ferrofluids, where nano-scaled particles are suspended in an appropriate carrier liquid. This leads to additionally heat and mass transfer phenomena, such as the Soret effect [11].

Figure 3 shows \( Q \) as a function of \( \Delta T \) for the sample APG 513A_OLD. Without an applied magnetic field the typical behaviour of thermal convection with the change from conduction to convection at \( \Delta T_{\text{crit}} \) is shown whereas \( \Delta T_{\text{crit}} \) is again 32 °C. The progress of the heat flux curve is nearly identical to the curve of the sample APG 513A_NEW as shown before which is explained by the fact that the basic fluid properties are similar. The difference of the samples is given by the microstructure of the fluid. For the second fluid an increase of \( \Delta T_{\text{crit}} \) is observed due to the strong field dependent increase of its viscosity.
3. Conclusion

The experimental results presented here have shown that under certain circumstances the magnetoviscous effect can influence thermomagnetic convection. By applying a magnetic field the additional heat flux introduced by the magnetic force causes a reduction of $\Delta T_{\text{crit}}$. This situation occurs for the ferrofluid sample called APG 513A_NEW which shows no magnetoviscous effect. In contrast a significant magnetoviscous effect appears for the ferrofluid sample called APG 513A_Old which contains a contingent of large particles. For this sample $\eta$ increases by a factor of 4.4 for a magnetic field strength of 30 kA/m. This behaviour of $\eta$ causes a shift of the transition point, where the heat flux characteristic changes from conduction to convection, to higher values of $\Delta T_{\text{crit}}$.

For investigations of thermomagnetic convection it should be considered that for certain circumstances the magnetoviscous effect can arise in ferrofluids which will affect the experimental results of the threshold of convection.

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