An experimental study of dynamic flow of nanofluid with different concentrations

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Abstract: Current reported data of nanofluid concentration is almost all based on TEM observation, which is in a static situation. No data of dynamic concentration during flow is reported. In the present study, an experimental measurement based on nuclear magnetic resonance (NMR) of monitoring the dynamic concentrations of nanofluid flow is carried out. It is demonstrated that the ferrofluid with Fe_3O_4 as its nanoparticles coated with surfactant as a special type of nanofluid can be used as T2 contrast agent in NMR scanning as well as a magnetic and thermal sensitive nanoparticle solution that would enhance heat transfer.

Key words: nanofluid, dynamic concentration, NMR

1. Introduction

Nanofluid has already been widely used in further enhancement of thermal performance of working fluid, such as in porous media.[1,2] Among these different type of nanofluid, magnetic nanofluids (or ferrofluids), which exhibit both magnetic and fluid properties, is even more promising. Magnetic nanofluids have many applications in electronic devices [3], mechanical engineering [4], materials science [5], analytical instrumentation [6], medical science [7], heat transfer [8], optics [9] and Art [10].

Magnetic nanofluids play an important role in different heat transfer phenomena, such as natural convection, forced convection, pool boiling, flow boiling, and pulsating heat pipes. [11] But different authors may have different explanations on the heat transfer enhancement mechanisms. And all the conclusions are drawn on the base of static magnetic nanofluids characteristics. However, the characteristics are dynamic in the real heat transfer process, especially the concentrations of magnetic nanofluids will change along with the time and position, which may have great influence on the heat transfer. Since the size limit of nanoscale particles, the only way to study the concentration of nanofluid is using high-resolution optical devices such as TEM or ultrasonic, while the dynamic concentration of nanofluids is very difficult to measure in such cases. Thus even though we can see a lot of articles and researches on static concentrations, dynamic concentration has never been deeply studied.[12,13] People would assume that the concentration would remain constant during the flow, and would record the whole thermal performance as a result of a certain concentration. However, we would never know the intrinsic character of a nanofluid when flowing. A new method is put forward based on the Nuclear Magnetic Resonance (NMR).

So, in order to further understand the heat transfer enhancement mechanism of magnetic nanofluids, the dynamic concentration of magnetic nanofluids is experimentally investigated using NMR method in present study. And this study would also provide a good support on the numerical simulation of nanofluid with mesoscopic methods such as LBM.

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2. Experimental Method

As with nanofluid, we are using a special nanofluid, ferrofluid, in our experiment. Ferrofluid is a functional liquid with strong magnetic properties from the stably dispersed magnetic particles. The ferrofluid we use has Fe_3O_4 nanoparticles, and contain oleic acid as its surfactant. These particles are dispersed in Sodium Dodecyl Sulphate (SDS), with the final size within the range of 9-10nm, and hydraulic diameter of 12nm.

Our current work is based on the Philip 3T achieva NMR machine, with 3 Tesla magnetic field and 128MHz Radio Frequency. The scanning has a resolution of around 0.22×0.22mm. The investigation is hoped to be combined into one solution to measure the ferrofluid flow through porous media in the future, scanning and measurement of ferrofluid.

In our static scanning of ferrofluid, we are using a series of different concentrations of ferrofluid, filled into small test tubes. We investigated pure water, SDS water solution at four times the Critical Micelle Concentration (CMC), 0.01%, 0.03%, 0.05%, 0.07%, 0.09%, 0.1%, 0.11%, 0.2%, 0.3%, 0.4% and 0.5%, all in volume percentage. The series of test tubes are tied together and put into a thermal insulated water bath tank, with a PID controlled heater. So the test tubes with the ferrofluid inside would be slowly heated up from around 10°C to 40°C and get NMR scanned step by step.

Then in dynamic experiment, around 15 Litre of ferrofluid with a few selected volume concentrations are put into a circle, using DC powered pump pumping ferrofluid through the pipe into the NMR machine. Also, with the temperature set at some certain points, we can separately see the difference of signal from flowing ferrofluid and another scanning made immediately after the pump is shut off.

Basic parameter in NMR is the T1/T2 value. The longitudinal (or spin-lattice) relaxation time T1 is the decay constant for the recovery of the z component of the nuclear spin magnetization towards its thermal equilibrium value. The transverse (or spin-spin) relaxation time T2 is the decay constant for the component of perpendicular magnetization field. The nuclei, mainly hydrogen atom in water, would release signals during its magnetization process, which would decay away when it goes back to equilibrium distribution. So T1 and T2 become the most important relaxation time in the progress with different tissues or fluid situations.

In general,

$$M_z(t) = M_{z,eq} - \left[M_{z,eq} - M_z(0)\right]e^{-t/T_1} \quad (1)$$

$$M_{xy} = M_{xy}(0)e^{-t/T_2} \quad (2)$$

This is why we can see the signals going as below after taking logarithm of the signals,

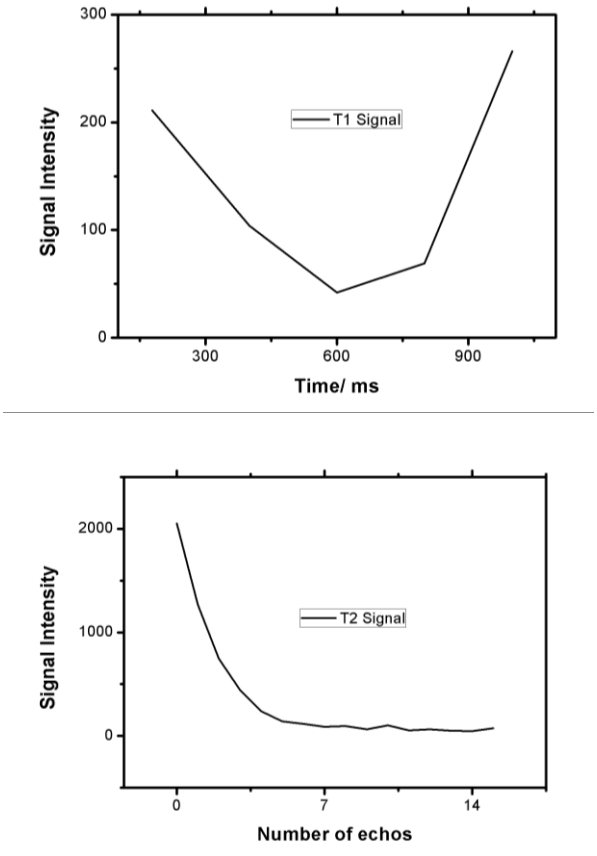

Fig. 1: Variations of Signals as Time

Since each signal would obey this principle in NMR scanning, we can see that the T1/T2 become unique in certain flow situation. And as we mentioned above, ferrofluid and other nanofluid has been shown to be a very good T2 contrast agent, which means that it could

strongly affect the signals under T2. So when taking logarithm of the T2 signals S in Equation 2, we can get the equations as below,

$$\log(S) = -t / T_2^* + \log(M) \qquad (3)$$

It would be an obvious linear relationship between logarithm of signal and the time t. And the slope would be

$$k = -1 / T_2^* \qquad (4)$$

Please be aware that the T2 we use here is T2 star instead of T2, which means a minor correction in real case to the principle equation. For in real cases, the distribution of resonance frequency can lead to a loss of signal, which causes the signals decaying faster than ideal, and a smaller T2 measured, that is the T_2^*. And they hold the relationship as

$$\frac{1}{T_2^*} = \frac{1}{T_2} + \frac{1}{T_{inhom}} = \frac{1}{T_2} + \gamma \Delta B_0 \quad (5)$$

Thus we can measure the slope in logarithm line of signals, and get different T_2^* as a unique parameter of a certain situation. And if we get a database of T_2^* at different temperature and concentration, which would be demonstrated below, we will be able to use it to relocate the dynamic concentration in complex nanofluid flows.

With the millions of data received, we can analyse the flow velocity and water/nanofluid distribution.[14] Even though the flow rate can be very low and affect the accuracy of our result, and the noise would also increase with the high resolution, by taking several scans each time and get average can largely increase the accuracy as well.

If we want to relocate the concentration gradient, we have to make a database on the changes of T_2^*, with temperature and concentration. However, we have found that high concentrations of ferrofluid could block the signals since metal-cored particles could affect the resonance of hydrogen atom. And the upper limit is considered as 1% volume percentage, according to our previous research.

In our later experiment, we use the slop we get directly from the logarithm of signal instead of T_2^*, which is the k as we mentioned in Equation 4. By calculating different k at different temperature and concentration, we can plot a few other lines about the trend in which k is changing against temperature and concentration, which would be the basis of our later analysis.

When we compare the slope, or decaying speed of the signal to temperature, at a certain concentration, we can see a perfect line just matches the theory as in Figure 2. So we can say, that the slope goes down linearly with the temperature rising. This is the result we expect according to theory, and it shows that NMR do shows the difference of different temperature. Also, we do plot another series of lines in which k is compared against concentrations, as is in Figure 3.

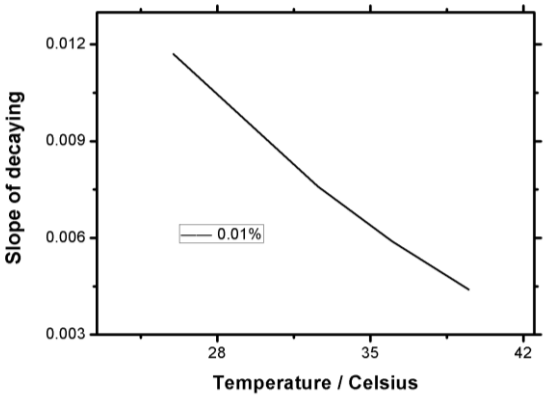

Fig. 2: The slope k against Temperature

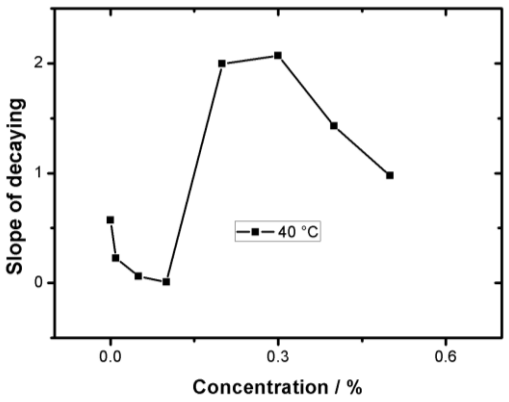

Figure 3: The Slope k against Concentration (T=40°C)

Figure 4 is much more interesting since

what it should be is that the slope k should always going down with concentration going up, however, it shows that slope rises sharply after the concentration of 0.1% volume and then goes back down again. The reason for the phenomena is still under discussion, however, we can use the first part of Figure 3 or 4, when concentration is lower than 0.1% volume, and it is always going as theory. And when we take logarithm no only on signals but also on the concentrations, according to principle, we expect that we can get a map like Figure 4. And we will see that we also get a few perfect matching lines in our experiments as in Figure 4, at three selected temperatures, especially under 0.1% volume.

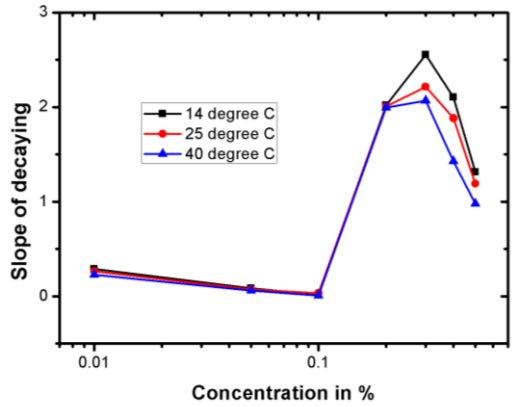

Figure 4: The slope k against Concentrations

3 Results and Discussion

That is all for the preparation work we've done before we do scanning on real case nanofluid flow. Even though it is described at the beginning that ferrofluid under 1% volume can be seen under NMR, what we want to measure is the decaying speed of signals, instead of pure signals. When the concentration is between 0.1% and 1% volume, we still can see the signal, however, the signals would be decaying so fast that we cannot get to precisely measure the decaying time with the limit of time gap in the NMR machine. Therefore, as with our final step, a few selected concentrations lower than 0.1% volume is chosen and put into scan. The ferrofluid is pumped into a pipe and then go through the NMR machine. And from the basic mask for the velocity image, with velocity unit mm/s, as can be seen in Figure 5. Figure 5 is a 128*128 pixels square, showing the cutting profile directly of a pipe with ferrofluid flowing inside. The pipe seems very small in this image, however, from this image, we can see that the velocity in a circle, which is the pipe under NMR, gets brighter in the centre and darker in the outer ring, which obeys the theory of flow through a cylinder pipe. This is the minimum task we should reach in our experiment as to measure the velocity of nanofluid flow.

And if we analyse further into T_2^* of the fluid inside the pipe, we can see a very clear difference between flowing fluid and non-flowing fluid. As we assume from basic theory, if a fluid is flowing, then the signal sent from the atoms at time zero would be moving away at time one, and makes the signal decaying faster than it should be in static. If we put the two lines in Figure 6 together, we can easily see that we get a very good result in this section, as the gradient of the non-flowing line matches perfectly with the patterns in Figure 4, while the flowing line decays faster than non-flowing, and the velocity can be the key role in affecting this.

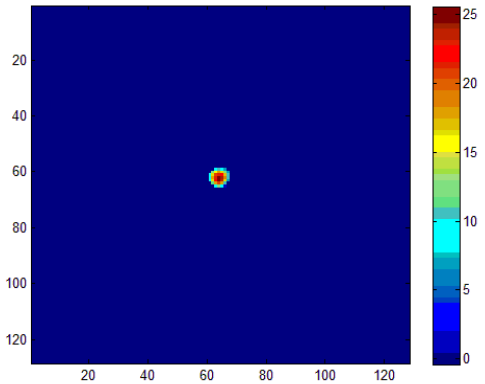

Figure 5: Velocity of Flow (T=17°C)

Also, Figure 6 shows that the black line dropping sharply after 6ms. Since the mechanism of NMR is to give a magnetic pulse to the fluid, as is called the Radio Frequency (RF), the atom would react and give out signals to be measured every time step. However, if the fluid is flowing, then the

active atom would flow away from the previous situation, where the coil of NMR machine locates, and the distance would result in a faster decay of signal received by the coil. It is really excited that we can get this result perfectly matches the theory. Since the sharpening of the slope is caused by the velocity of flow, and the higher speed nanofluid is going, the sharper it would be. This would give us the opportunity to make further develop on the signals of ferrofluid under different concentration, temperature and flowing velocity. And all these parameters will be shown as the slope of the decaying line.

Furthermore, it can be seen from Figure 5 that the diameter of the tube is about 8 pixels in current resolution. So if we divide the area into an 8×9 squares, we can find that the tube as is a circle, is internally tangent to the square. And each part has its own slope, which shows its concentration gradient when we assume the temperature across the tube remains equal. And we can see a roughly plotted figure below as Figure 7. The vague image is caused by an enlargement of the pixels, while the exact result of each point is still very accurate from the matrix we get. And it does give us a clearly result that the concentration is higher in the centre part since the brighter part in the figure means lower slope. This result means that we can definitely see the concentration gradient within the tube when it's flowing. And we can also see that instead of more previous assumptions by researchers that the ferrofluid would be equally dispersed, the real case is, that the concentration is higher in the centre area, and forms a good gradient.

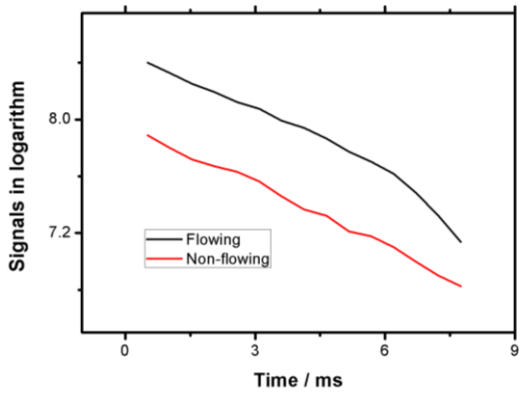

Figure 6: Comparison of Decaying Signals under Flowing and Stopped fluid

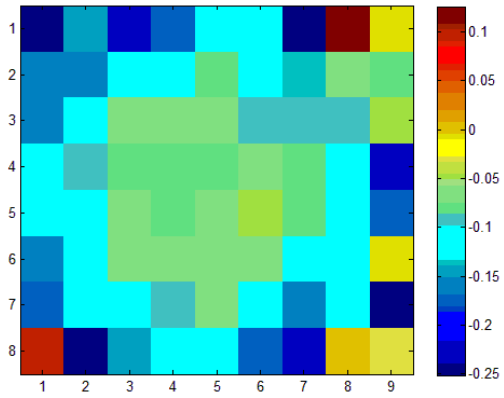

Figure 7: Slope (Concentration) Distribution

4 Conclusions

Nanofluid flow is getting more and more important in heat transfer enhancement. And dynamic concentrations of nanofluid may strongly affect the performance than static concentration assumptions. So measuring the dynamic concentration of nanofluid would be a very interesting research point.

With all the data we have achieved by now, we can have this reasonable guess that dynamic nanofluid flow through porous media can be measured better using NMR than previous approach. We know that the NMR signals of ferrofluid, with its main property of being a fluid, can be changing gradually with the change of temperature.[16,17] What's more, we can get velocity of fluid flow from NMR in a very precise way, as is discussed many authors and proved by this paper as well. That is why NMR can be so effective in measuring dynamic nanofluid flow, since it could give out different signals under different temperature and different concentration. What more important, is that they all shows a unique pattern of changing with temperature and concentration (below 0.1% volume). So, if we could get a database with signals of ferrofluid from NMRI at different temperature and different concentration, then we will be able to achieve the temperature and concentration distribution from an unknown flow pattern by simply analysing the signals and compare with

the database. Just as in Figure 7, we can have a clear view of the concentration gradient in dynamic flow inside a pipe. And we are assuming it would also be the same case in porous structure.

However, we still face some serious problem in NMR. First of all, metal and electricity is not allowed in the scanning, which may affect the ability to bring test rigs into NMR machine. Secondly, pressure gradient measurement in fluid flow is still not very obvious in applied NMR. Thirdly, even though the scanning resolution can go higher and higher into 20μm×20μm, noise would also sharply increase during this process, and would increase the error in signal measurement that we would still have anyway. At last, our concentration still cannot go higher than 0.1% volume, and the temperature could never reach any point close to boiling.

This method may also allow investigation on improving the fluid flow through porous media by applying bionic technology such as capillary effect[11,15] and osmosis effect. Following experiments might lead to a better understanding of the processes which allow devices like heat pipes to adjust flow rate.

References

[1] J. Koo, C. Kleinstreuer, Laminar nanofluid flow in microheat-sinks, International Journal of Heat and Mass Transfer, 2005, 48(13), 2652-2661

[2] Jie Li, Clement Kleinstreuer, Thermal performance of nanofluid flow in microchannels, International Journal of Heat and Fluid Flow, 2008, 29(4), 1221-1232

[3] B. Ghasemi, S.M. Aminossadati, Periodic natural convection in a nanofluid-filled enclosure with oscillating heat flux, International Journal of Thermal Sciences, 2010, 49(1), 1-9.

[4] B. Wright, D. Thomas, H. Hong, et al., Magnetic field enhanced thermal conductivity in heat transfer nanofluids containing Ni coated single wall carbon nanotubes, Applied Physics Letters, 2007, 91(17), 173116.

[5] H. V. Thakur, S. M. Nalawade, S. Gupta, et al., Photonic crystal fiber injected with Fe3O4 nanofluid for magnetic field detection, Applied Physics Letters, 2011, 99(16), 161101.

[6] S. D. Soelberg, R. C. Stevens, A. P. Limaye, et al., Surface Plasmon Resonance Detection Using Antibody-Linked Magnetic Nanoparticles for Analyte Capture, Purification, Concentration, and Signal Amplification, Analytical Chemistry, 2009, 81 (6), 2357-2363.

[7] M. Salloum, R.H. Ma, D. Weeks, et al., Controlling nanoparticle delivery in magnetic nanoparticle hyperthermia for cancer treatment: Experimental study in agarose gel, International Journal of Hyperthermia, 2008, 24(4), 337-345.

[8] X. Q. Wang, A. S. Mujumdar, Heat transfer characteristics of nanofluids: a review, International Journal of Thermal Sciences, 2007, 46(1), 1–19.

[9] V. Mahendran, J. Philip, An optical technique for fast and ultrasensitive detection of ammonia using magnetic nanofluids, Applied Physics Letters, 2013, 102(6), 063107.

[10] S. Kodama, Dynamic ferrofluid sculpture: organic shape-changing art forms, Communications of the ACM, 2008, 51(6), 79-81.

[11] M. Mohammadi, M.Hohammadi, M.B. Shafii, Experimental investigation of a pulsating heat pipe using ferrofluid (magnetic nanofluid), Journal of Heat Transfer, 2011, 134(1), 014504

[12] S. Chakraborty, S. K. Saha, J.C. Pandey, S. Das, Experimental characterization of concentration of nanofluid by ultrasonic technique, Powder Technology, 2011, 210(3), 304-307

[13] Yimin Xuan, Qiang Li, Heat transfer enhancement of nanofluids, International Journal of Heat and Fluid Flow, 2000, 21(1), 58-64

[14] Bottomley, P.A., H.H. Rogers, and T.H. Foster, NMR imaging shows water distribution and transport in plant root systems in situ. Proceedings of the National Academy of Sciences, 1986. 83(1): p. 87-89.
[15] Richards, L.A., Capillary conduction of liquids through porous mediums. Physics, 1931. 1(5): p. 318-333.
[16] Richards, L.A., Capillary conduction of liquids through porous mediums. Physics, 1931. 1(5): p. 318-333.
[17] Holz, M., S.R. Heil, and A. Sacco, Temperature-dependent self-diffusion coefficients of water and six selected molecular liquids for calibration in accurate 1H NMR PFG measurements. Physical Chemistry Chemical Physics, 2000. 2(20): p. 4740-4742.