Thermal Properties of Magnetic Nanofluids

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Indira Gandhi Centre for Atomic Research [IGCAR], established in the year 1971, under the **Department of Atomic Energy, Government of India.**

The centre is engaged in **scientific research and advanced Engineering of sodium cooled Fast Breeder Reactor [FBR] technology**.

Apart from nuclear technology, the centre is also engaged research in basic sciences.

Staff strength is **2463** including **1037** Engineers and Scientists

The annual outlay of the Centre is around 670 million rupees (11 million Euro) towards the R & D activities.

Nanoscience activities

CoFe2O4 nanocrystal Synthesis (2008)

- S.Ayyappan, … J. Philip "Effect of surfactant monolayer on reduction of Fe_3O_4 nanoparticles under vacuum" (**Journal of Physical Chemistry C 2008 - In press**)
- S.Ayyappan, J. Philip & B. Raj "Tuning the size and magnetic properties of $CoFe_2O_4$ nanocrystal by varying Co^{2+} ion activity" (**Mat.Letters**)
- S.Ayyappan, J. Philip and B. Raj "Effect of solvent dielectric constant on the size and magnetic properties of precipitated $CoFe_2O_4$ nanoparticles" (**MCP**)
- S.Ayyappan, J. Philip & B. Raj "Solvent polarity effect on physical properties of $CoFe_2O_4$ nanoparticles" (**J.Phys.Chem**)
- Simple approach to synthesis monodispered metal nanoparticles **(To communicate)**

Synthesis (2007)

- G. Prakash, J. Philip, B. Raj "Effect of Digestion Time and Alkali Addition Rate on the Physical Properties of Magnetite Nanoparticles" **J. Phys. Chem. B** 2007, 111, 7978-7986

- G.Prakash, S.Ayyappan, T.Jayakumar, J. Philip & B. Raj "A simple method to produce magnetic nanoparticles with enhanced alpha to gamma-Fe2O3 phase transition temperature" **Nanotechnology** 17 (2006) 5851-5857.

- J. Philip, .. B. Raj. "Effect of thermal annealing under vacuum on the crystal structure, size and magnetic properties of ZnFe2O4 nanoparticles" **Journal of Applied Physics**, 102, 054305, 2007

- G.Prakash, J. Philip & B. Raj "Effect of divalent metal hydroxide solubility product on the size of ferrite nanoparticles" **Materials Letters** 61 (2007) 4545–4548
- G.Prakash, .., J. Philip & B. Raj "Effect of initial pH and temperature of iron salt solutions on formation of magnetite nanoparticles during co-precipitation" **Materials Chemistry and Physics** 103 (2007) pp 168-175

- S.Mahadevan, G.Prakash, J.Philip, B.P.C.Rao, T.Jayakumar "X-ray diffraction based characterization of magnetic nanoparticles in presence of goethite and correlation with magnetic properties" **Physica E**. 39 (2007) 20–25

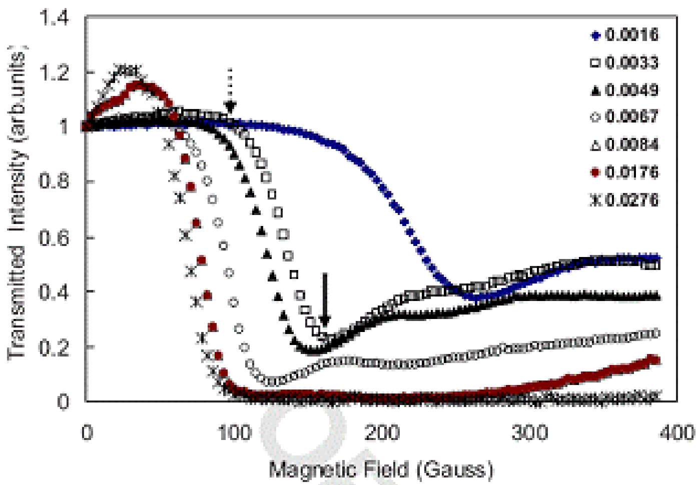
Light scattering in Nanofluids (2008)

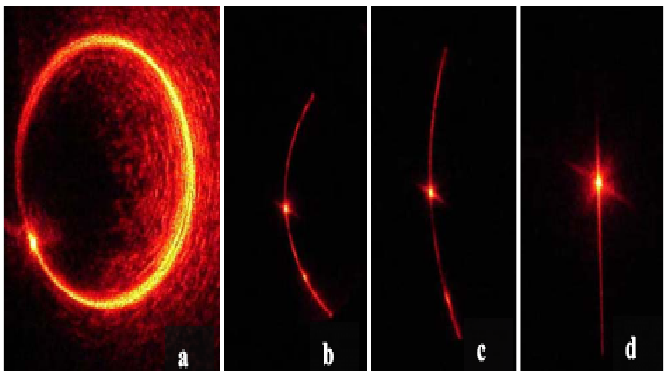
- J.M.Laskar, J. Philip, and Baldev Raj “Light Scattering in a magnetically polarizable nanoparticle suspension”
  Phys.Rev E, 78, 031404 (2008)

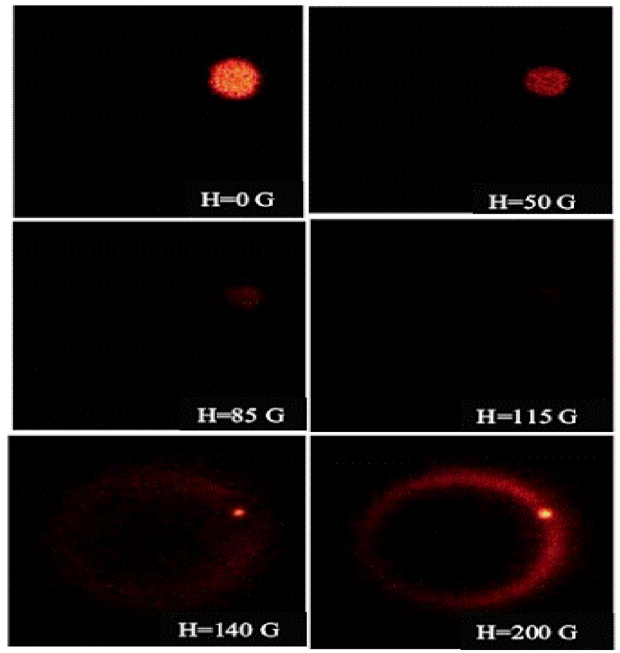
- J. Philip, J.M.Laskar and Baldev Raj “Magnetic Field induced extinction of light in a suspension of Fe3O4 nanoparticles”
  Applied Physics Letters 92, 221911 (2008)

  * Virtual Journal of Nanoscale Science & Technology June 23, 2008

- Kinetics of structural transitions (Phys.Rev E)







Colloidal forces measurement

- J. Philip, G.Prakash, T.J.Kumar, P.K.Sundaram & Baldev Raj, “Three distict scenario under polymer-surfactant and colloid interaction” **Macromolecule** 36 (2003) 9230-9236

- J.Philip, G.Prakash, T.J.Kumar, P.K.Sundaram , Baldev Raj “Stretching and Collapse of Neutral Polymer layers under Association with Ionic Surfactants” **Physical Review Letters** 89 (26) 2002 268301

- J.Philip, T.J.Kumar, P.K.Sundaram , Baldev Raj, O.M.Monval “Effect of polymer-surfactant association on colloidal force” **Physical Review E** 2002 66 011406:1-8

- J.Philip, G.Prakash, T.J.Kumar, P.K.Sundaram , O.M.Monval & Baldev Raj, “Interaction between emulsion droplets in the presence of polymer surfactant complexes” **Langmuir** 2002, 18, 4625-4631.

Applications

- J.Philip, T.J.Kumar, P.K.Sundaram , Baldev Raj

  “Tunable Optical Filter” **Meas. Science & Tech.** 14 (2003) 1289-1294

- J.Philip, C.B.Rao, T.J.Kumar & B.Raj

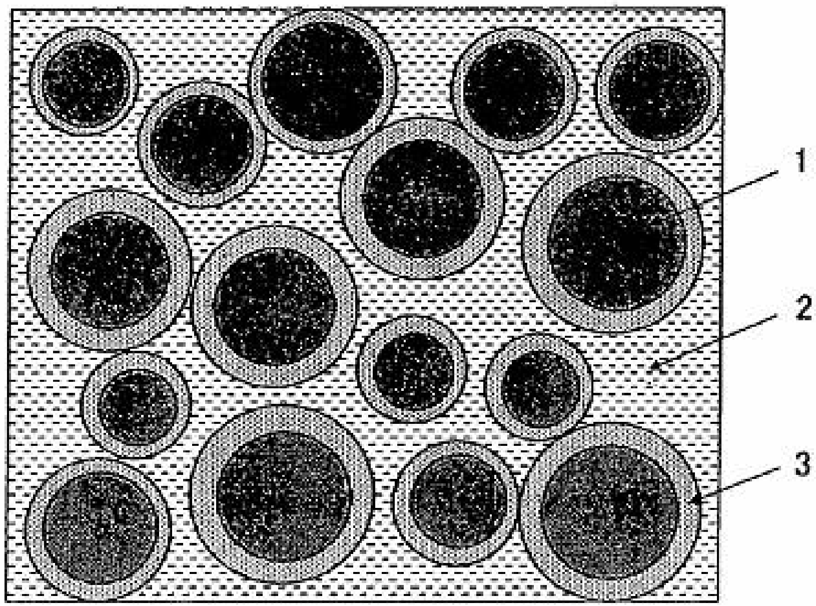
  “A new optical technique for detection of defects in ferromagnetic materials and components” **NDT&E International**, 33 (2000) 289-295

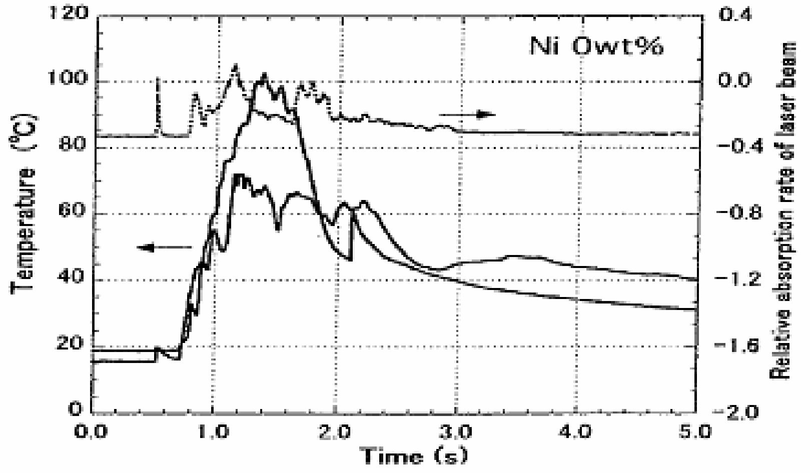
- J.Philip, C.B. Rao, B.Raj & T.J.Kumar

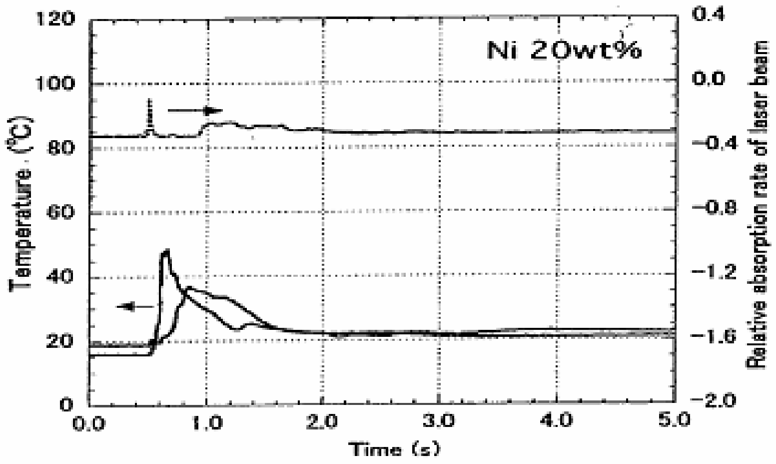
  "An optical technique for the detection of surface defects in ferromagnetic samples” **Measurement Science & Technology**, 10 (1999) N71- 75

Reducing Na Reactivity with water

Pub. No.: US 2006/0054869 A1







- Without Ni nanoparticles, the temperature rise was 70-102^{0}C

- With Ni np of 20 wt%, the temperature rise was 37-50^{0}C

Change in temperature with time and change in the outputs of the displacement sensor (change in the concentration of the reaction product)

Thermal properties of Nanofluid (2007-2008)

- J.Philip, P.D.Shima.. B. Raj, "Evidence for enhanced thermal conduction through percolating structures in nanofluids"
  Nanotechnology 19 (2008) 305706

- J.Philip, P.D.Shima,B. Raj, "Nanofluid with tunable thermal properties"
  Applied Physics Letters 92, 043108 (2008)
  ***Nature Nanotechnology, Research Highlights 8 February 2008**
  **Virtual Journal of Nanoscale Science & Technology* Feb. 11, 2008
  * *Appeared as* editor's choice NanotechWeb, Institute of Physics in the UK *News story(S&T) Hindu Daily May 8, 2008
  *News Institute of metals and minerals Review, No.6 June 28, pp28-31

- J.Philip, P.D.Shima, B. Raj, "Experimental Evidence for enhancement of thermal conductivity under clustering"
  Applied Physics Letters 91, 2007, 203108
  **Virtual Journal of Nanoscale Science & Technology 16, Nov 26, 2007.*

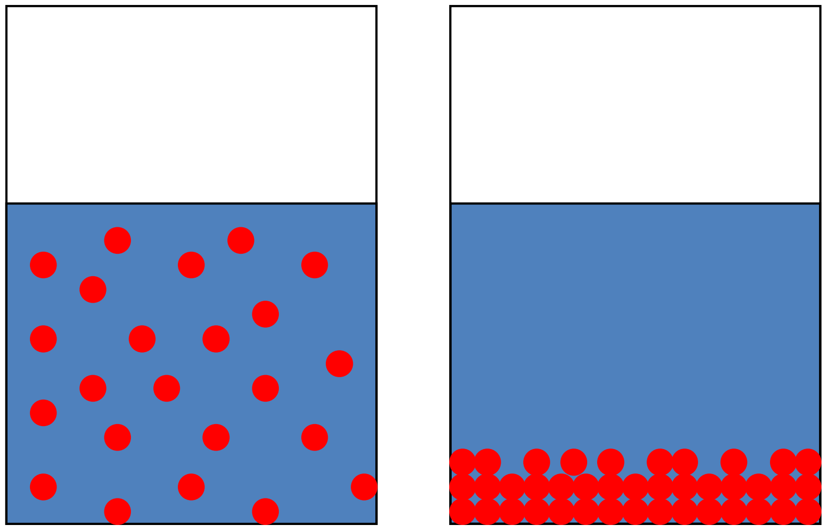
- Karthekeyan, J. Philip & B. Raj " Thermal properties of CuO nanofluid"
  Materials Chemistry and Physics Vol. 109 (2008) pp 50–55

Outline

- **Nanofluid Basics**
- **Thermal properties of Nanofluids**
- **Applications**
- **Mechanism of heat conduction in Nanofluid**
- **Magnetic Nanofluids**
- **Thermal conductivity results**
- **Conclusions**

Nanofluids

Nano-particles suspended in a carrier fluid

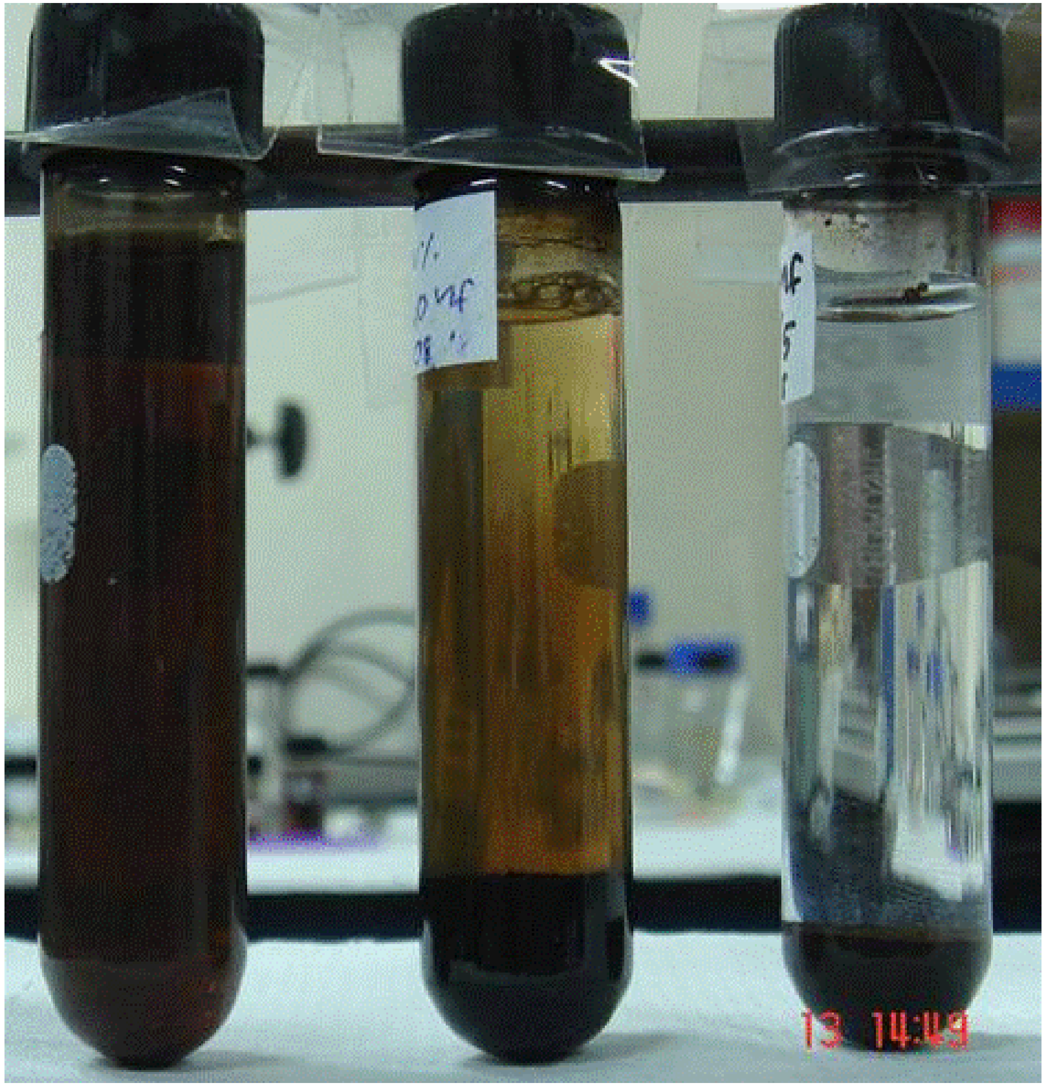


- Metallic NP (Cu, Ag, Au, Al….)
- Ceramics [oxides Al_2O3, CuO, carbides SiC, nitrides AlN, SiN..]
- Metal Oxides
- Nonmetallic (CNT, graphite)

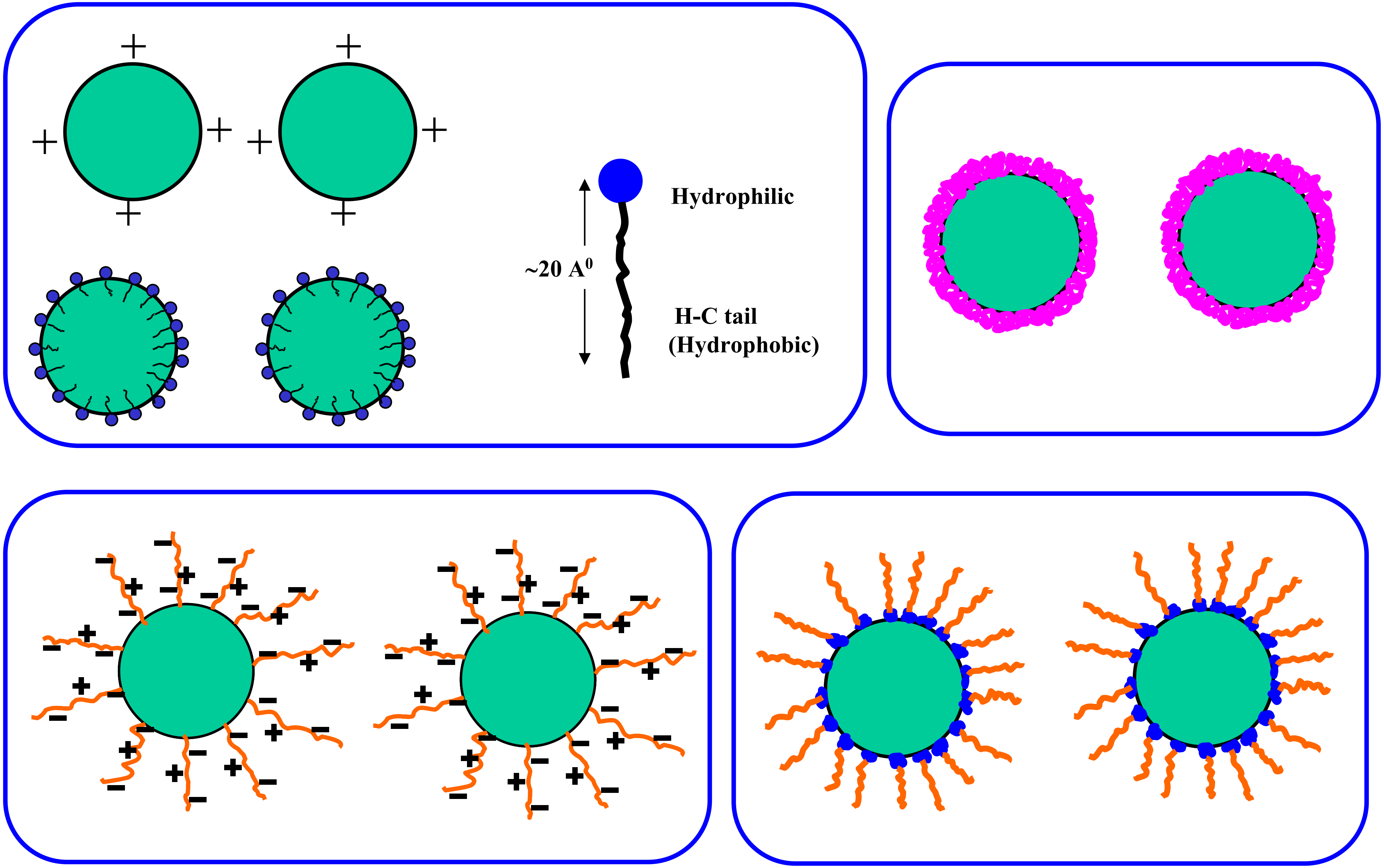
$$V_0 = \frac{2\Delta\rho g d^2}{9\eta}$$

For $\Delta\rho$ = 4100 Kg/m^2, g =9.81 m/s^2, η= 3 m.Pa.s, ϕ = 0.1 and d = 6.7 nm, sedimentation velocity V_0 = 0.002m/sec.

CuO nanofluid



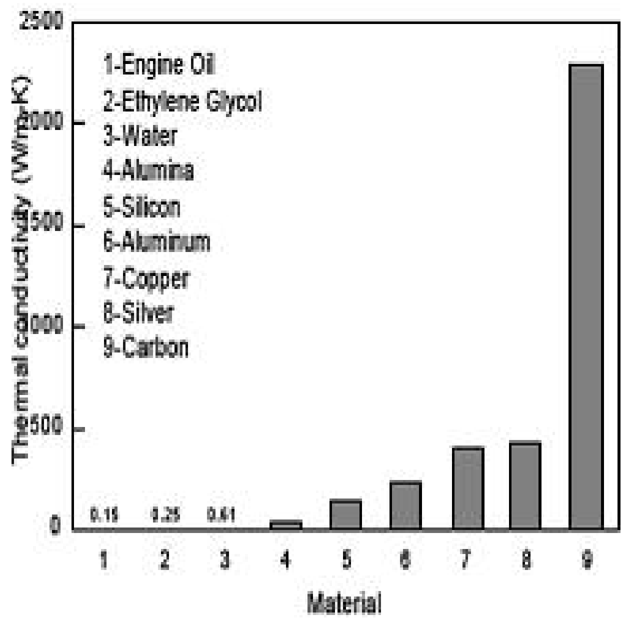
Stabilization methods



Why Nanofluids?

Traditional heat transfer fluids have low thermal conductivity compared to solids.

Material	Thermal Conductivity (W/m-K)
Liquids:	
• **Water**	**0.613**
• **Ethylene Glycol**	**0.253**
• **Engine Oil**	**0.145**
Metals:	
• **Silver**	**429**
• **Copper**	**401**
• **Aluminum**	**237**
Nonmetallic solids:	
• **Diamond**	**3300**
• **Carbon**	**2300**
• **Silicon**	**148**
• **Alumina (Al2O3)**	**40**



Thermal conductivity of typical materials

S.U.S.Choi, J.AEastman…..

Thermal properties of Nanofluids

H. Masuda, 1993

Netsu Bussei 7 〔4〕 (1993) 227-233

超微粒子分散による液体の熱伝導率と粘性率の変化
（Al_2O_3, SiO_2, TiO_2 超微粒子の分散）

Thermal conductivity of water based oxide nanofluids

- At 4 vol.% particle loading, the observed k enhancement was

  ~30% for Al_2O_3

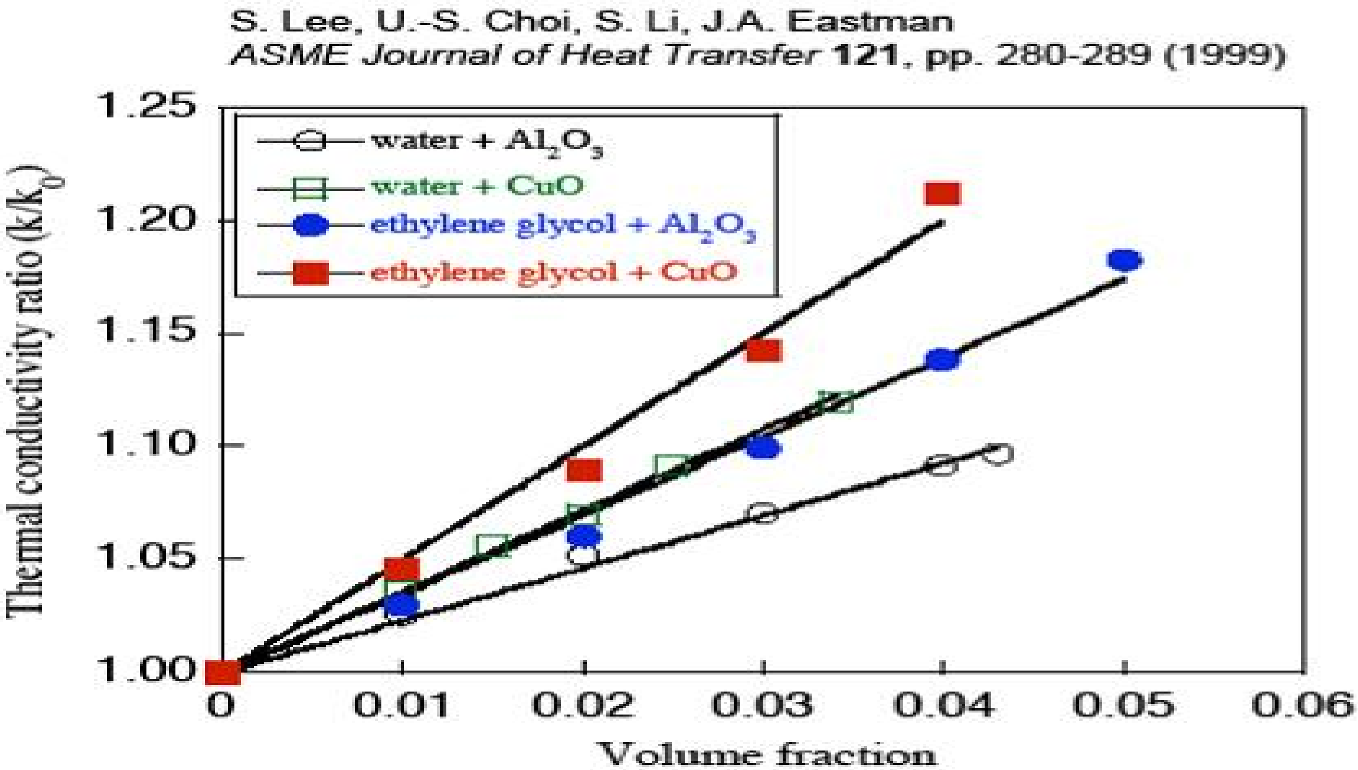
  ~10% for TiO_2

  ~1% for SiO_2

Thermal properties of Nanofluids

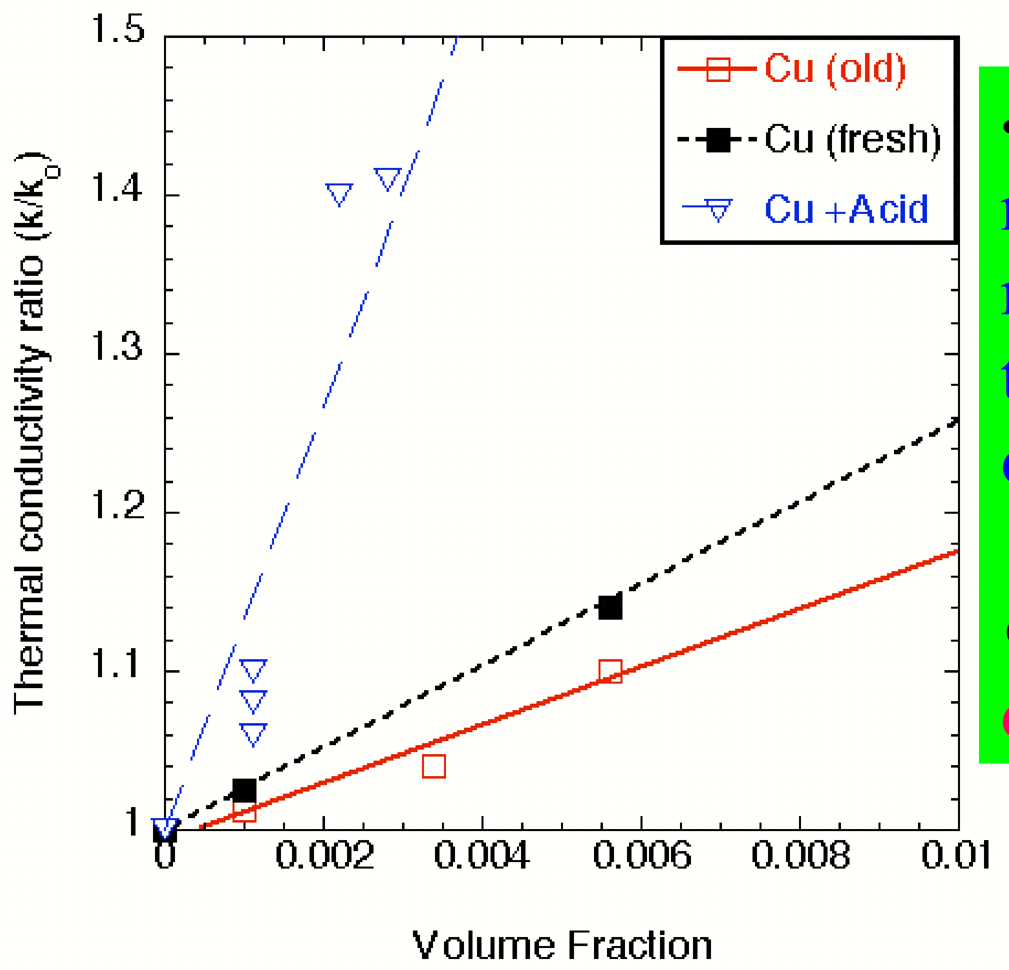
S. Lee, U.-S. Choi, S. Li, J.A. Eastman *ASME J. Heat Transfer* 121 (1999)

- Water and ethylene glycol based CuO than Al_2O_3 nanoparticles (k/kf ~1.08- 1.20)
- Larger enhancement in EG than water



Cu Nanofluid

J.A. Eastman *et al.*, *Appl. Phys. Lett.*, ***78, 718 (2001)***

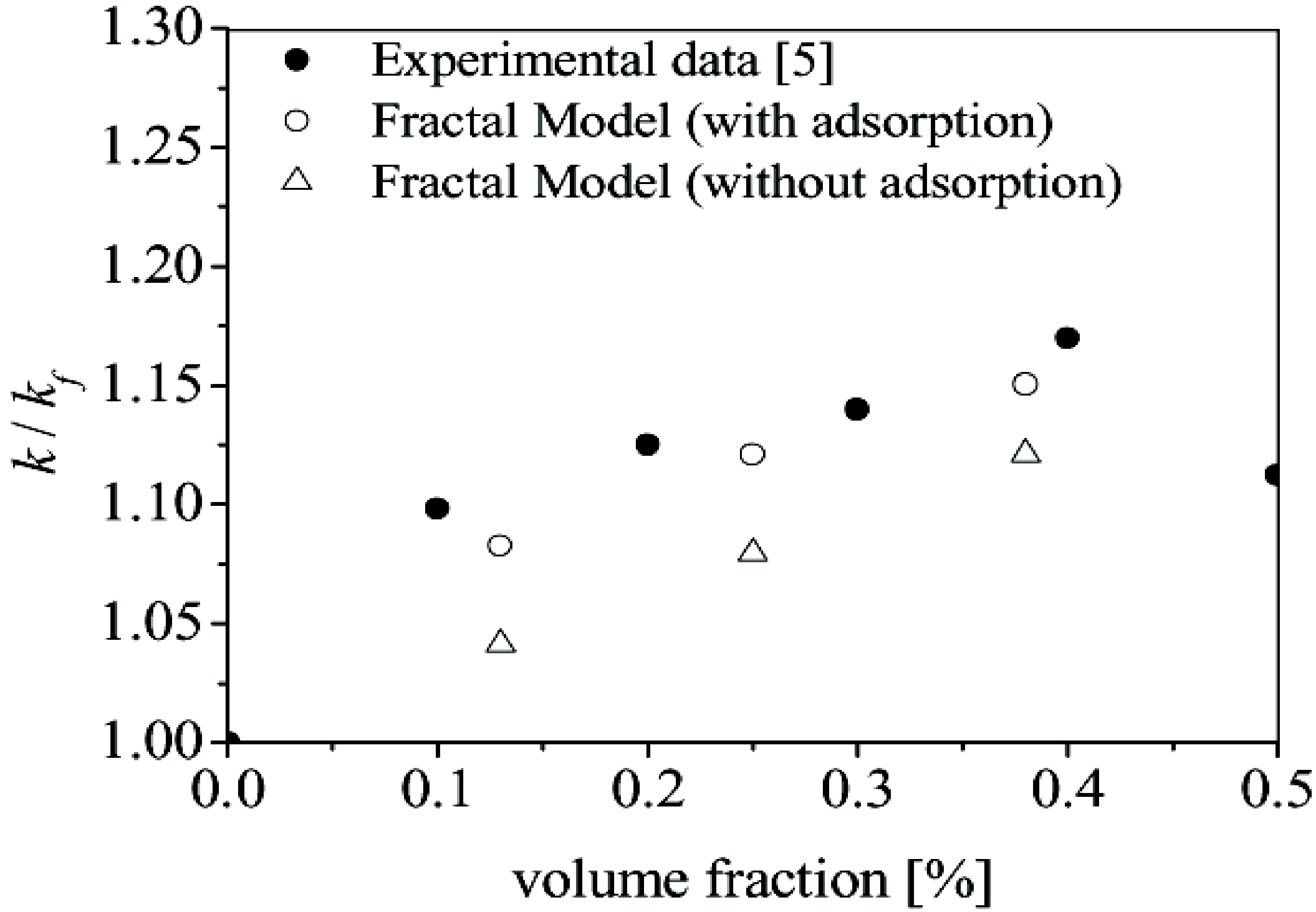


- Smaller diameter (10 nm) Cu nanoparticles produce much larger increase in *k* than larger diameter (30 nm) oxide nanoparticles

- Thioglycolic acid improves dispersion behaviour

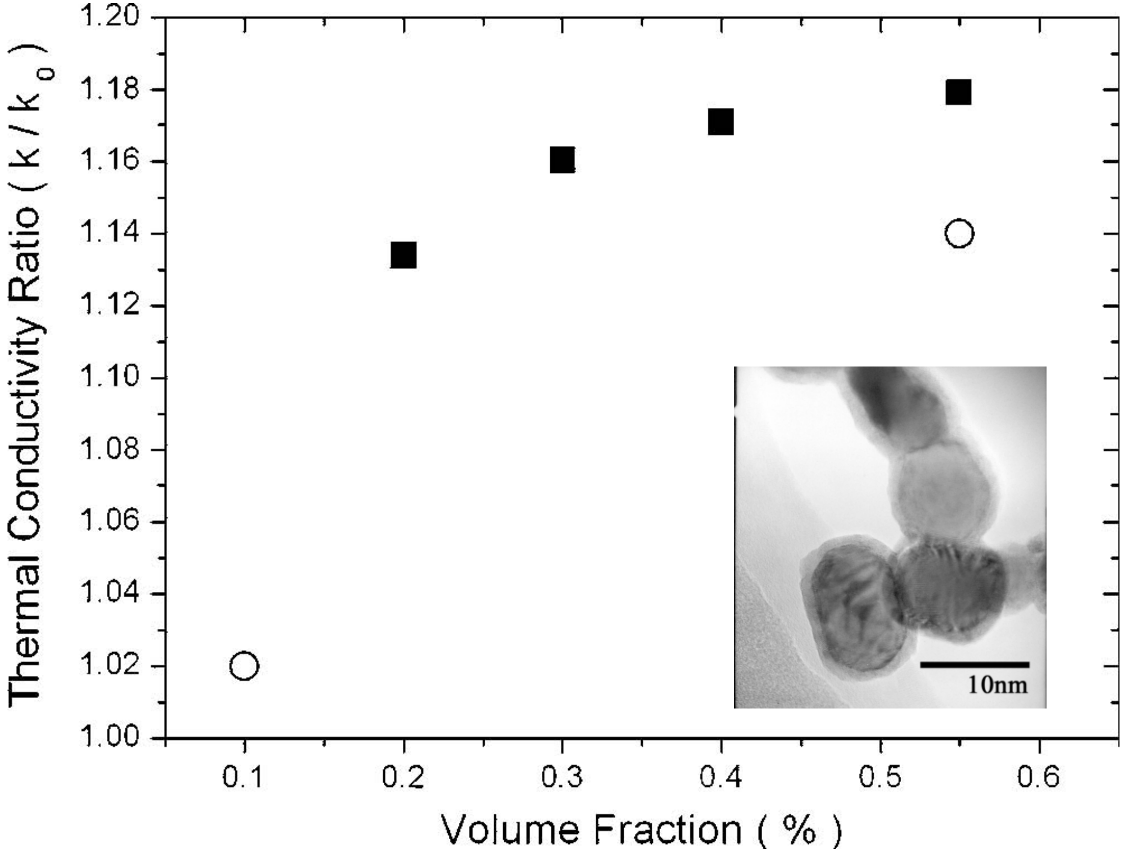
Zhou Wang, *Ann. Proc. Chin. Eng. Thermophysics*, 889 (2002)

0.4 vol.% CuO (50 nm particle size) in H_2O ~ 17% enhancement



Fe Nanofluid

T.-K. Hong, H-S. Yang, *J. Appl. Phys.*, ***97, 064311, (2005)***



- **Fe nanoparticles produced by chemical vapor condensation**

- **Behavior is similar to Cu (without added surfactant)**

- **Experimental studies show anomalous enhancement in the thermal conductivity in nanofluids.**

- **This area acquired a major thrust after the reports from Argonne National Laboratory that nanofluids containing copper oxide nanoparticles, exhibit enhancement in thermal conductivity (60% with 5 vol% of nanoparticles)**
[J. A. Eastman, S. U. S. Choi, S. Li, W. Yu, and L. J. Thompson, Appl. Phys. Lett. **78**, 718 2001].

- **Since then, there have been several reports of anomalous enhancement of the thermal conductivity of various nanofluids**

•Despite numerous studies, neither the magnitude or the mechanism of the thermal conductivity enhancement in nanofluids has been established.

•Reports show enhancement in the thermal conductivity ranging from anomalously large values to that are similar to or even less than the prediction of effective medium theory.

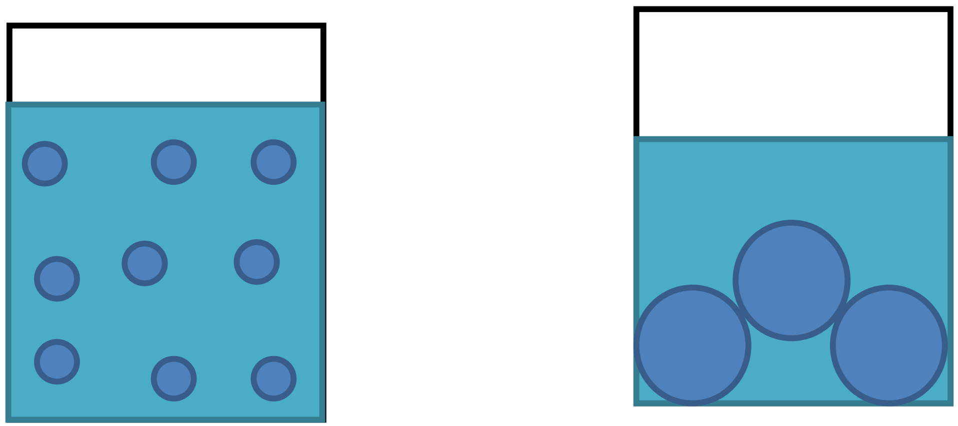
•Remarkably these discrepancies occur even for the same base fluid and the same nanoparticles.

•The situation in the field has been recently described as "investigations of the properties of nanofluids have reached the awkward situation of having a greater number of competing theoretical models than systematic experimental results" [J. Appl. Phys. **99**, 084308 2006]

Nano vs. Micron?

- **Nanoparticle dispersions show enhanced thermal conductivity**

Benefits of using NP
- **Stable dispersions**
- **Less clogging and abrasion**
- **Large surface area-to- volume ratio**



Applications Nanofluids Thermal Management

To cool

- Car engines
- Welding equipment
- High-power lasers, Microwave tubes
- Electronic Devices
- MEMS/NEMS (NF can pass through tiny channels)
- …

Benefits

- Efficient heat transfer.
- Reduce pumping power and operating costs.
- Miniaturize heat exchangers.
- Reduce heat transfer fluid inventory.
- Reduce emissions.
- Suited for applications in microchannel flow passages.

- **In heat exchangers that use conventional fluids, the pumping power must be increased by a factor of 10 in order to improve the heat transfer by a factor of 2.**
- **If a nanofluid (with thermal conductivity 3 times that of a conventional fluid) , the rate of heat transfer can be doubled without an increase in pumping power.**

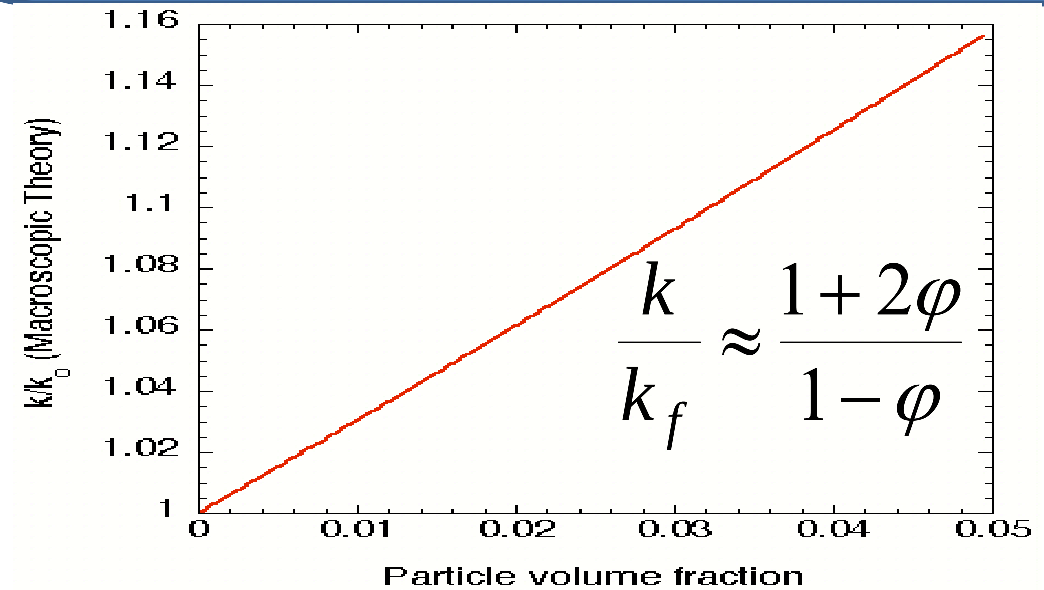
S.U.S.Choi, Argonne National Laboratory

Theoretical predictions

● The early attempts to explain the anomalous behavior in nanofluids were made with the classical theory of **Maxwell** for composite materials.

●This theory is applicable to statistically homogenous, isotropic composite materials with randomly dispersed spherical particles having uniform particle size

•Predicts **increase in conductivity in nanofluids is approximately independent of particle size and particle conductivity**



$$\frac{k}{k_f} \approx \frac{1+2\varphi}{1-\varphi}$$

A few data are in good agreement with effective media theory while other studies show anomalous behavior

Effective medium theory

- **Here, nanoparticles are assumed to be stationary or slowly moving, with the heat diffusing through the “effective medium” composed of particles and fluid.**

- **Because the thermal conductivity of solids is usually much greater than that of liquids, the particle-liquid–particle pathways can lead to faster heat conduction through the medium below the percolation threshold.**

- **For spherical particles, and at small the volume fraction of nanoparticles; $k/k_f = 1 + 3\phi$**

Heat transport by the Brownian motion of the particles.

- Some studies modeled heat transport based on the Brownian motion of nanoparticles.

- Also, Brownian velocity of the suspended particle induces a fluctuating hydrodynamic flow, which increases thermal transport.

- This heat transport may provide an alternative mechanism for the enhancement of thermal conductivity of nanofluids.

- Of course, both of these mechanisms may contribute to the thermal conductivity enhancement in nanofluids; the question is their relative magnitudes.

……. Brownian motion of the particles

- **A key weakness of Brownian transport is that the thermal diffusivity, D_T, of base fluid is several orders of magnitude larger than nanoparticle diffusivity, D_{NP}**

- D_T- measures the rate of the heat flow via thermal conduction
- D_{NP} - measures the rate of mass motion due to nanoparticle diffusion.
- **The nanoconvection velocities are of the order of thermophoretic velocities, which for most nanofluids are insignificant [as low as 10^{-9} m/s].**

- **Thus the magnitude of possible nanoconvection effects is negligible**

Liquid layering around the particles

- **The basic idea is that liquid molecules can form a layer around the solid particles and thereby enhancing the local ordering.**

- **Since phonon transfer in crystalline solid is very effective, such local ordering in the liquid can lead to enhanced heat transport.**

- **“Tunneling of heat carrying phonons” from one particle to another is proposed (Keblinski et al. 2002).**

- **The subsequent molecular dynamics simulation work concluded that those mechanisms do not contribute significantly to heat transfer (Xue et al. 2004).**

Ballistic **transport**

- **Diffusive transport mechanism may not be valid at nano-scales. Rather, the heat transport in the nanoparticles is more ballistic.**

•**So for ballistic transport or even in fast diffusive phonon transport, the**

solid particles will be essentially at a constant temperature thereby, providing the same boundary condition for heat flow in the liquid regions.

•**If the ballistic phonons initiated in one particle can persist in the liquid and get transmitted to another solid particle, the heat transport can significantly increase.**

•**The phonon mean free path in the liquid is typically small because local ordering is limited to few atomic diameters. Since, particles are constantly moving by Brownian motion, there is a possibility that somewhat coherent phonon transfer is possible even with low particle concentrations.**

Possible mechanism (Initial thinking)

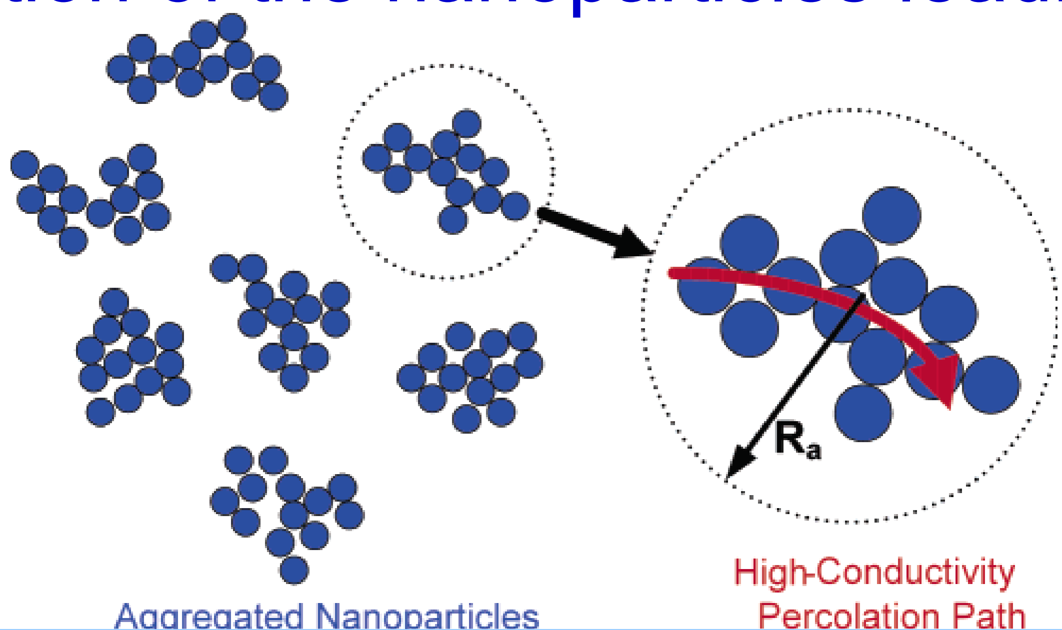
(P. Keblinski *et al.*, *ASME Journal of Heat Transfer* ***45*** (2002)

- Brownian motion
- Effect of particles on liquid local ordering (‘tunnelling’ of heat-carrying phonon from one particle to another)
- Ballistic rather than diffusive thermal transport in the particles
- Nanoparticle clustering

Current thinking

•Nanoconvection caused by the BM

•Due to the aggregation of the nanoparticles leading to local percolation



Aggregation will decrease the BM due to the increase in the mass of the aggregates whereas *k* can increase due to percolation effects in the aggregates

R.Prasher…NANO LETTERS 6 (2006) 1529; *Appl. Phys. Lett.* **2006**, 89, 143119.

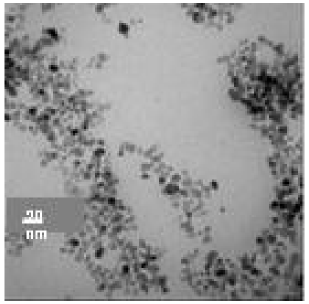
Models vs. experiments

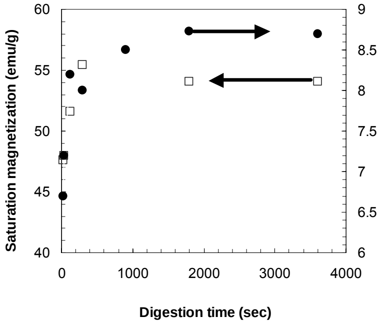
- **Large enhancements reported by several groups, can not be explained by effective medium theory**

- **Enhancements reported in many cases were beyond Maxwell limit of 3ϕ**

- **Greater number of models than systematic experimental studies.**

Magnetic nanoparticles



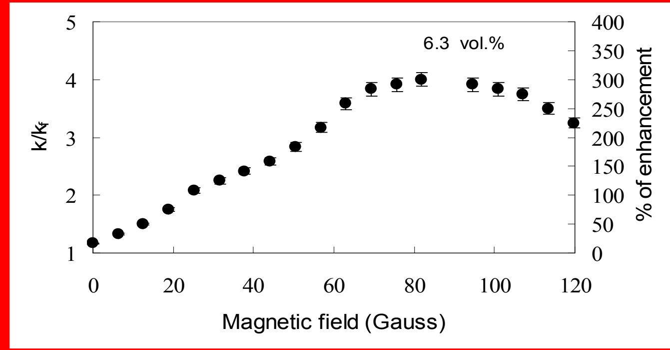


GP, JP.. J. Phys. Chem. C 2008

GP, JP.. J. Phys. Chem. B 2007

GP, JP.. Nanotechnology 2006

Seals

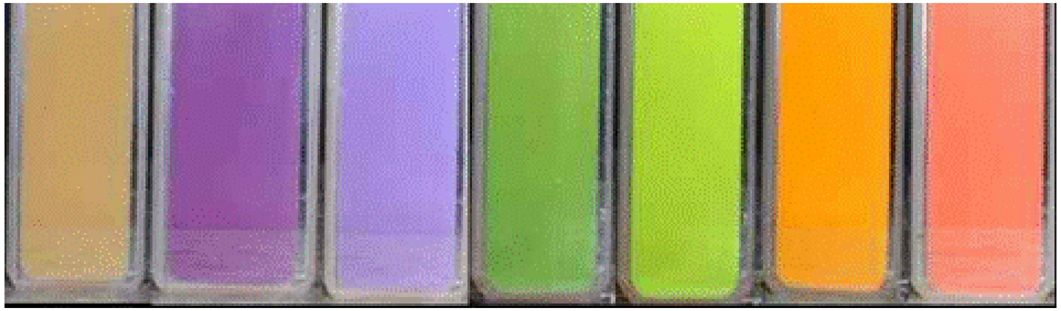


J Philip et al, Appl. Phys. Letts, 2007

J Philip et al, Appl. Phys. Letts, 2008

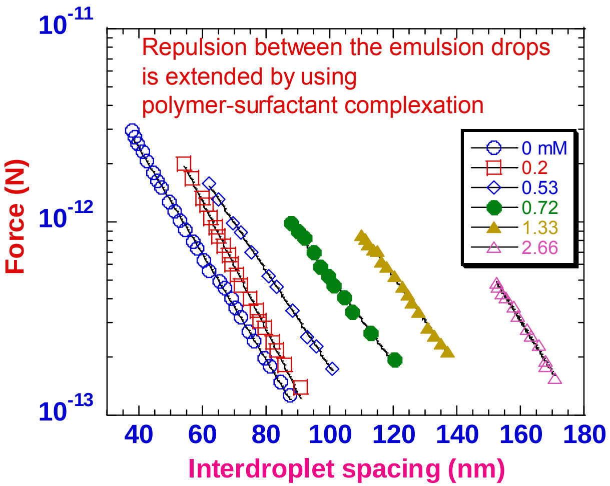
J.Philip et al. Nanotechnology, 2008

Applications:NDT Sensors, Tunable optical filter



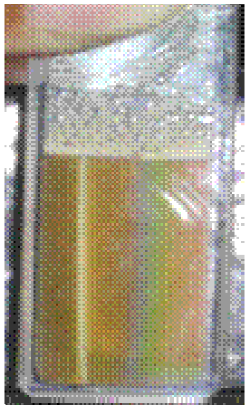
J.Philip…Baldev Raj; Patent 2002; Meas.Sci.Tech. 14, 2003

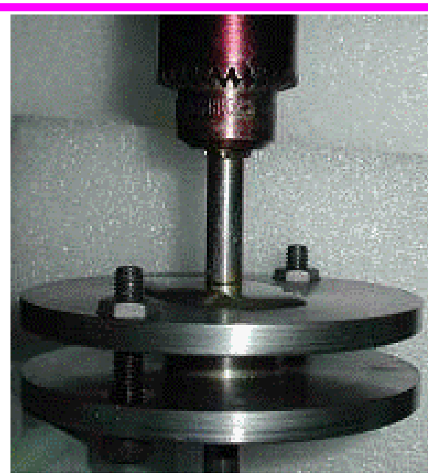
Nano emulsions (Colloidal Force measurement)



JP…B.Raj, Phys. Rev. Letts 2002

JP…B.Raj, Macromolecule 2003





J.Philip..B.Raj; Patents 186620 &186574 ; Meas.Sci.Tech. 10, 1999; NDT& E International , 33, 2000

Motivation

•To probe the role of Brownian motion and local percolation paths on heat transport

• We have chosen a stable colloidal suspension, which is magnetically polarizable.

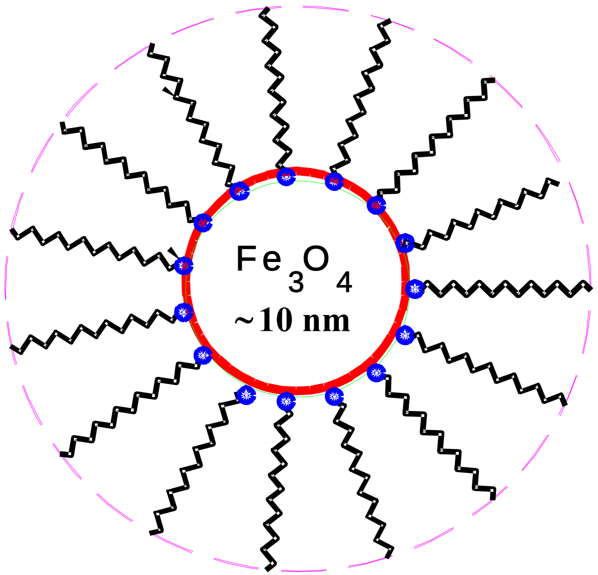
•The advantage is that the aggregation and the chain length could be precisely tuned from nano to micron scales.

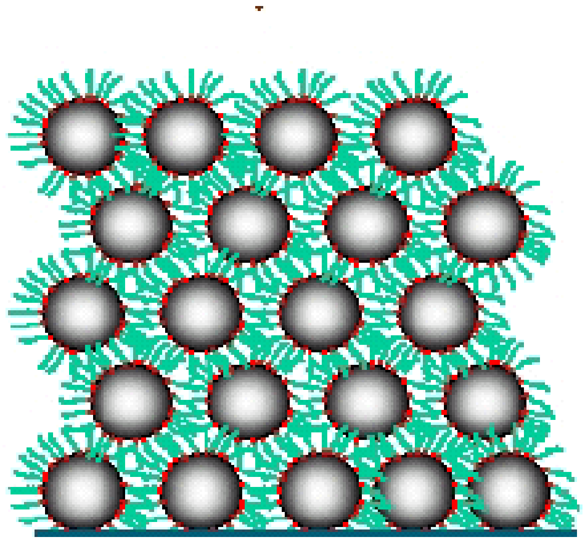
•This facilitate measurement of thermal conductivity under controlled aggregation in a particular direction (chain-like structures)

Magnetic Fluid (Ferrofluid)

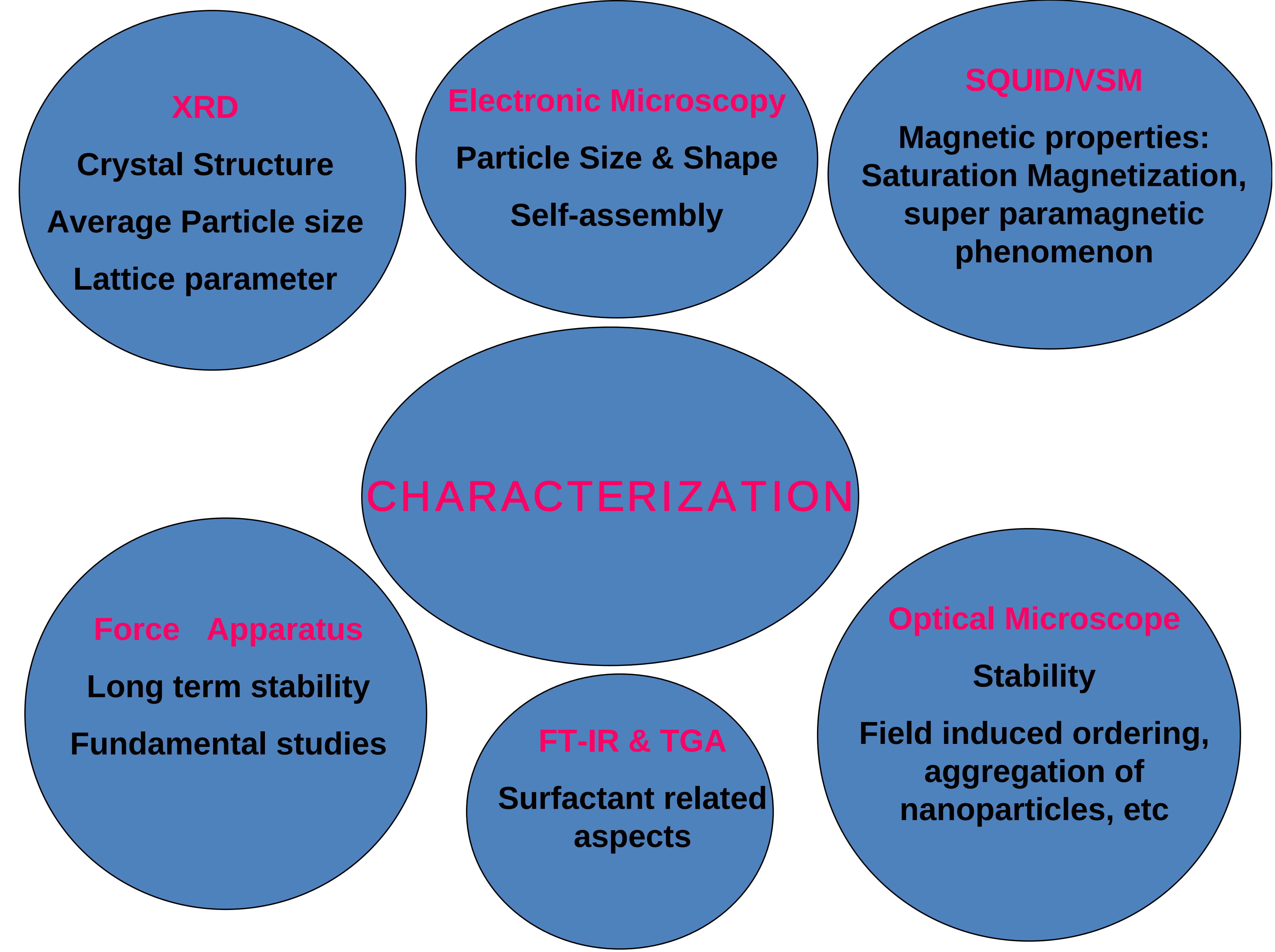
➢**Surfactant-coated Magnetite nano-particles (~7 nm) suspended in a carrier fluid**

Carrier liquids: Organic (oils, flurocarbon, etc.) and water

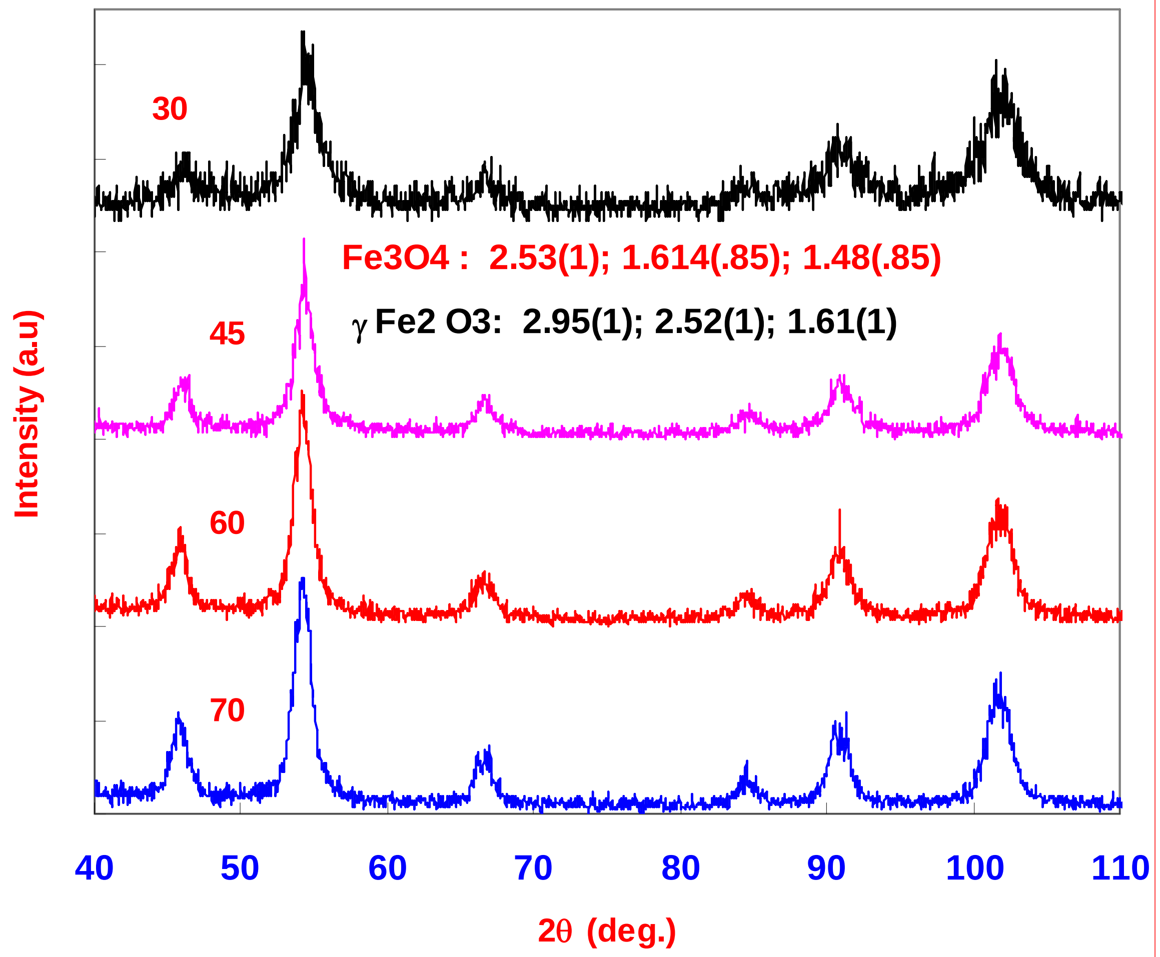




•Compatibility of surface active molecules with carrier fluid is important


CHARACTERIZATION
XRD
Crystal Structure
Average Particle size
Lattice parameter
Electronic Microscopy
Particle Size & Shape
Self-assembly
SQUID/VSM
Magnetic properties: Saturation Magnetization, super paramagnetic phenomenon
Force Apparatus
Long term stability
Fundamental studies
FT-IR & TGA
Surfactant related aspects
Optical Microscope
Stability
Field induced ordering, aggregation of nanoparticles, etc

XRD



Lattice Parameter

γ-Fe_2O_3	0.835 nm
Fe_3O_4	0.84 nm

The powder pattern of Fe_3O_4 and γ-Fe_2O_3 are very similar because both oxides exhibit closely the same crystallographic structure

- **Crystal structure**
- **Structural parameters**
- **Average particle size (D)**

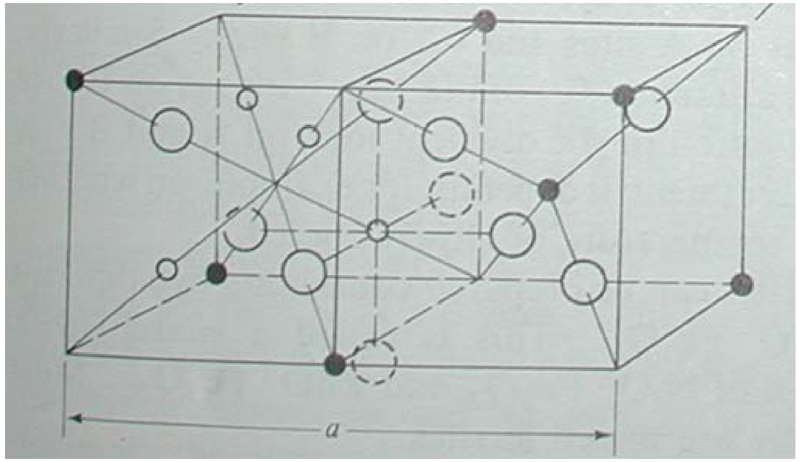
Scherrer formula

$$D = K\lambda / \beta \cos\theta \; ; \quad \beta \text{ is FWHM}$$

Fe_3O_4 crystal structure

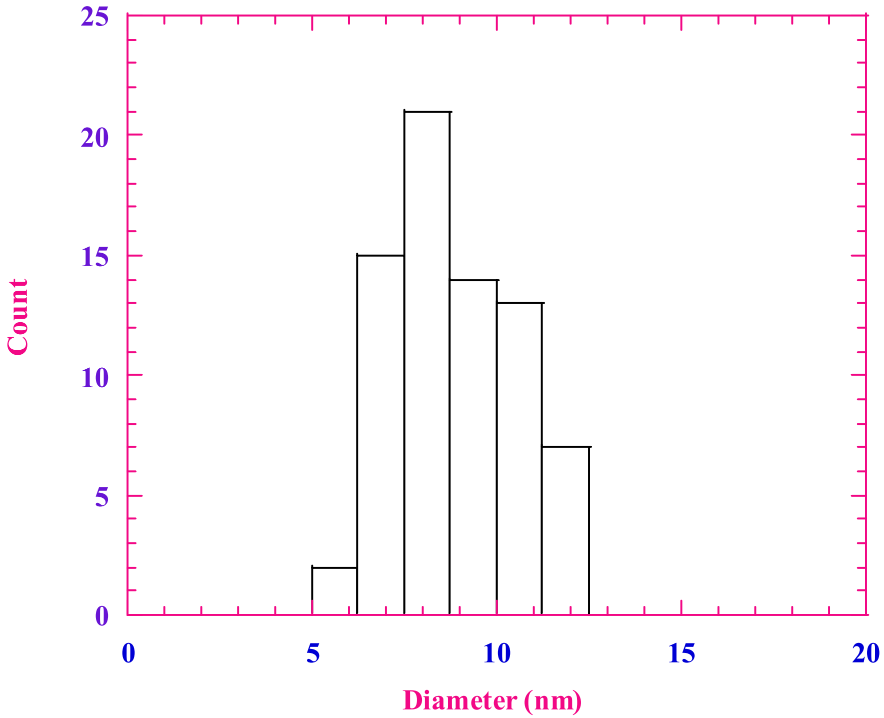
- Inverse spinel structure
- **O^{2-}** in cubic close-packed arrangement(32)
- Fe^{2+} occupies octahedral sites (8)
- Half of Fe^{3+} occupies octahedral and remaining half in tetrahedral (16).
- Electron spins of Fe^{3+} in octahedral and tetrahedral holes are **anti-parallel** .
- Electron spins of Fe^{2+} & Fe^{3+} in octahedral holes **align parallel** leading to net magnetization (***Ferrimagnetism***)

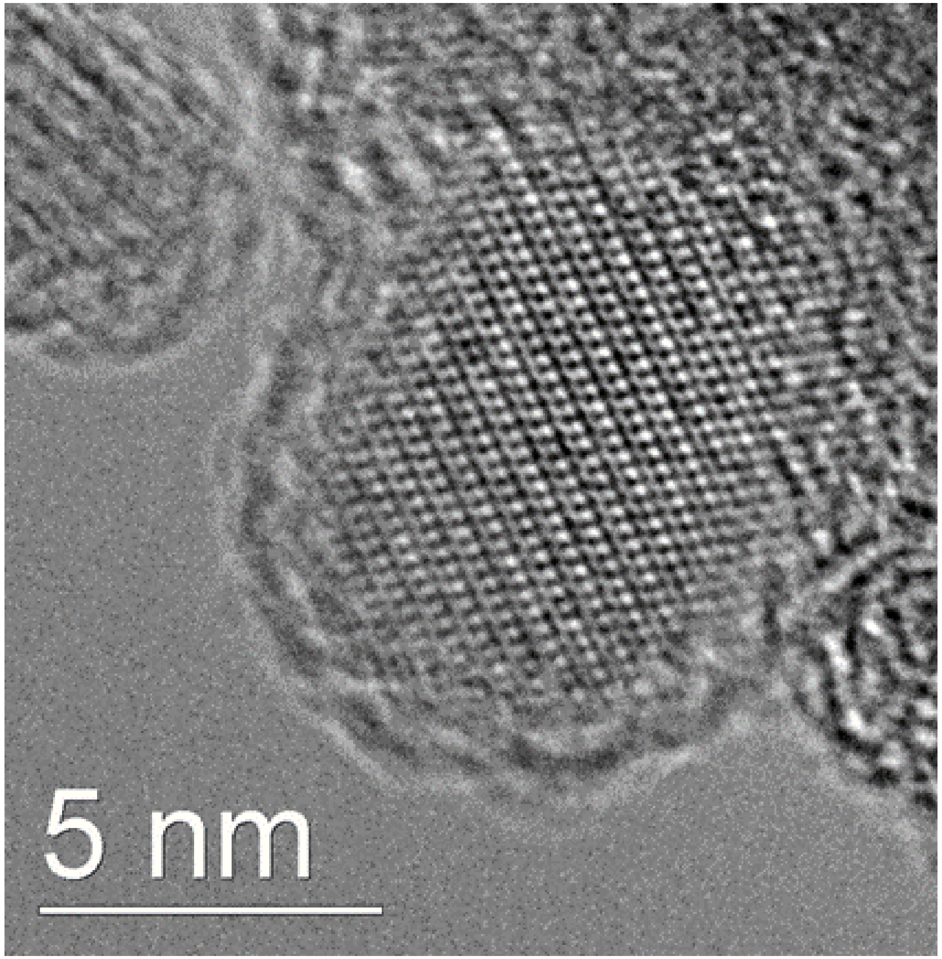
- O^{2-}
- Fe^{3+}
- Fe^{2+}



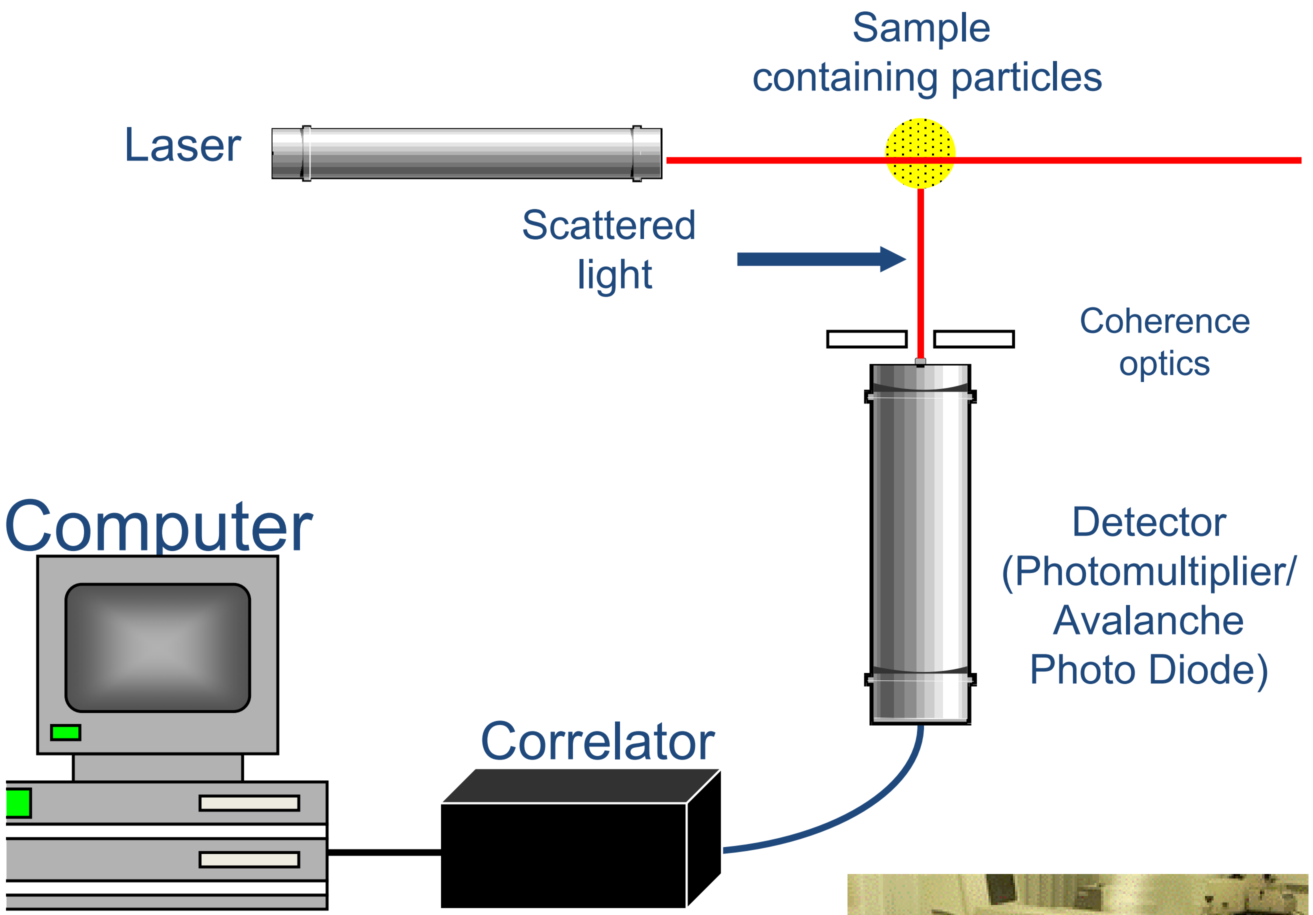
Fe^{3+} (T) Fe^{2+} (O) O^{2-}

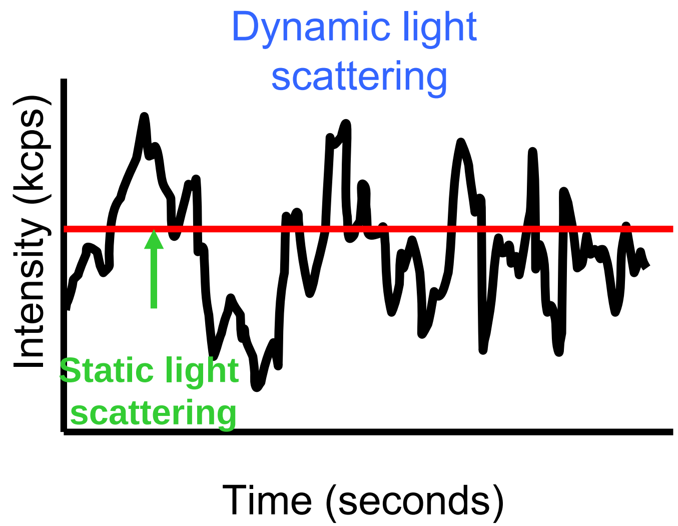
TEM

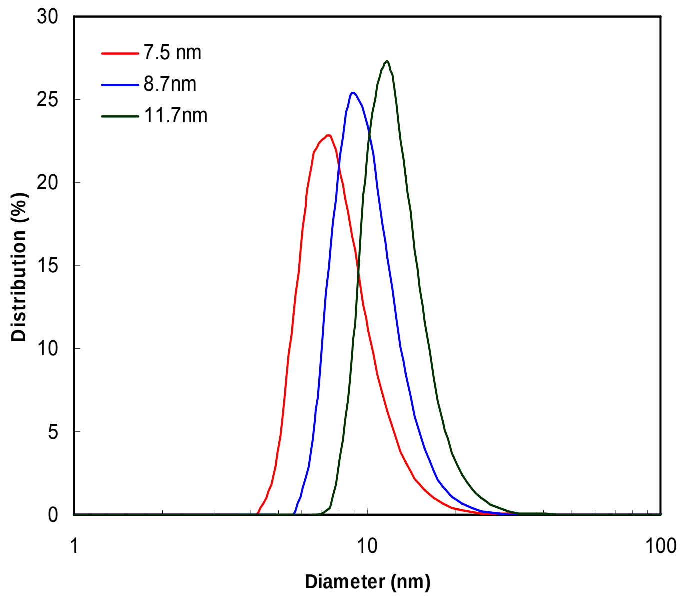




DLS

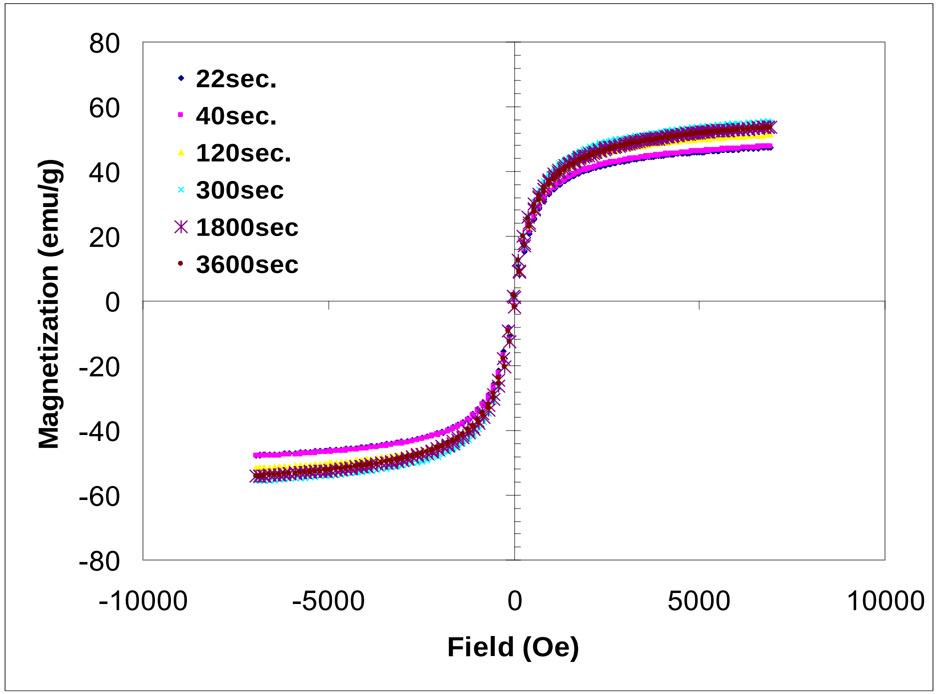

Sample
containing particles
Laser
Scattered
light
Coherence
optics
Detector
(Photomultiplier/
Avalanche
Photo Diode)
Computer
Correlator

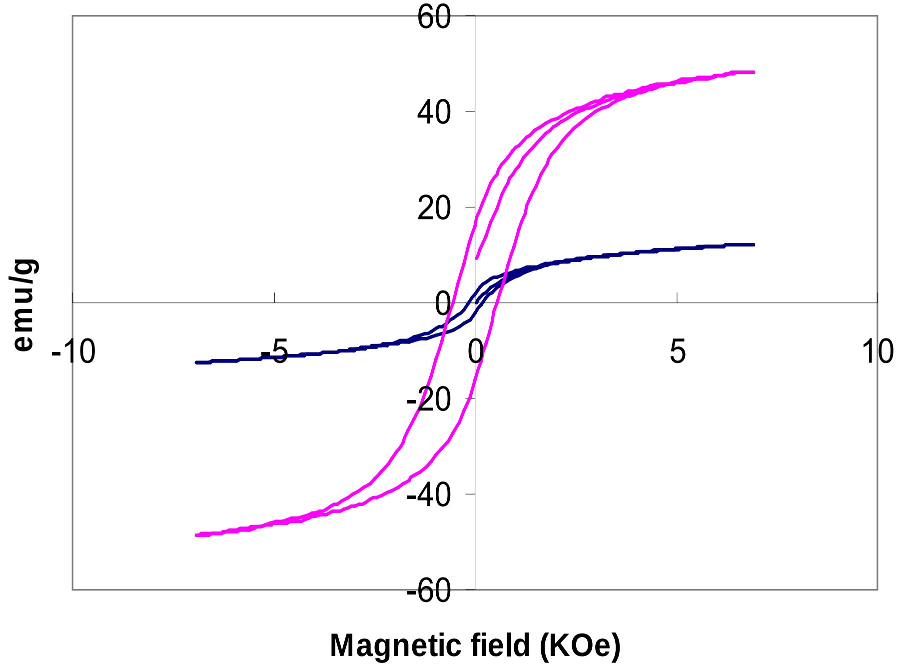

Dynamic light
scattering
Intensity (kcps)
Static light
scattering
Time (seconds)


7.5 nm
8.7nm
11.7nm
Distribution (%)
Diameter (nm)
0
5
10
15
20
25
30
1
10
100

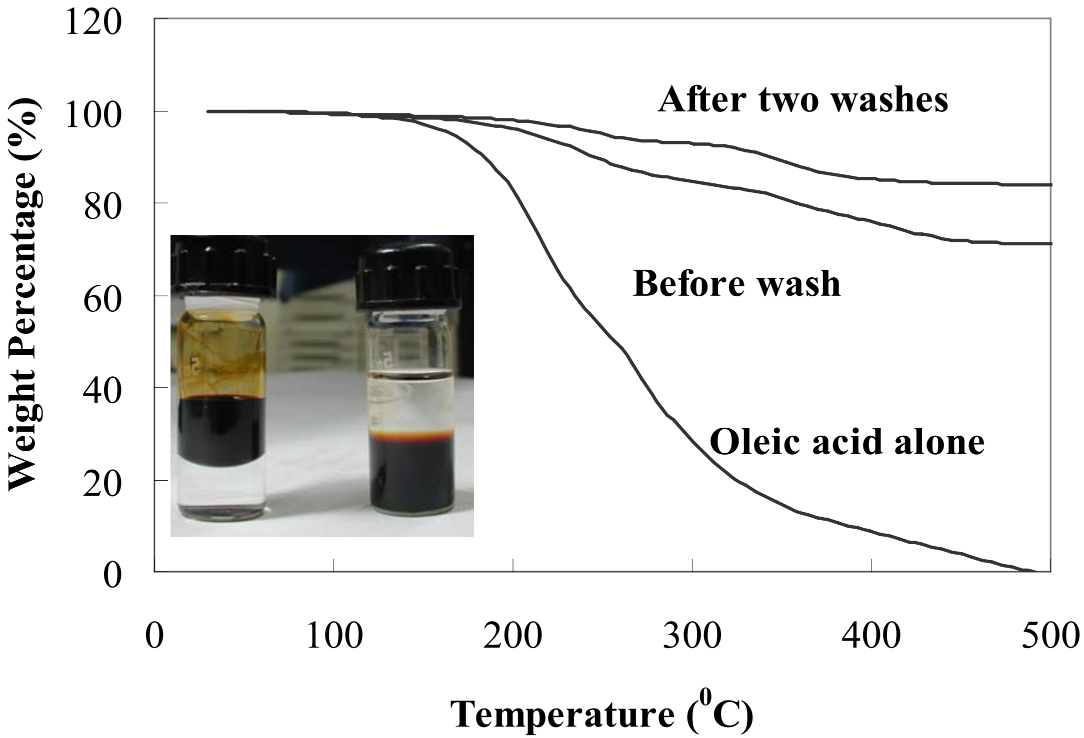
Magnetic Properties

- **Superparamagnetic nature**
- **Saturation magnetization**



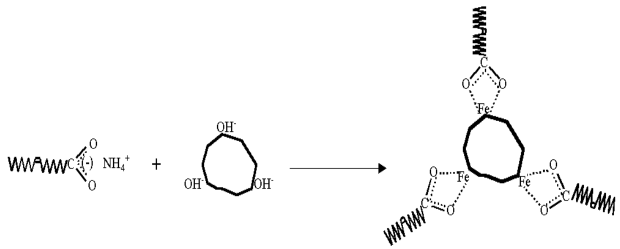


TGA



A two-step weight loss at ≈240 and ≈360°C.

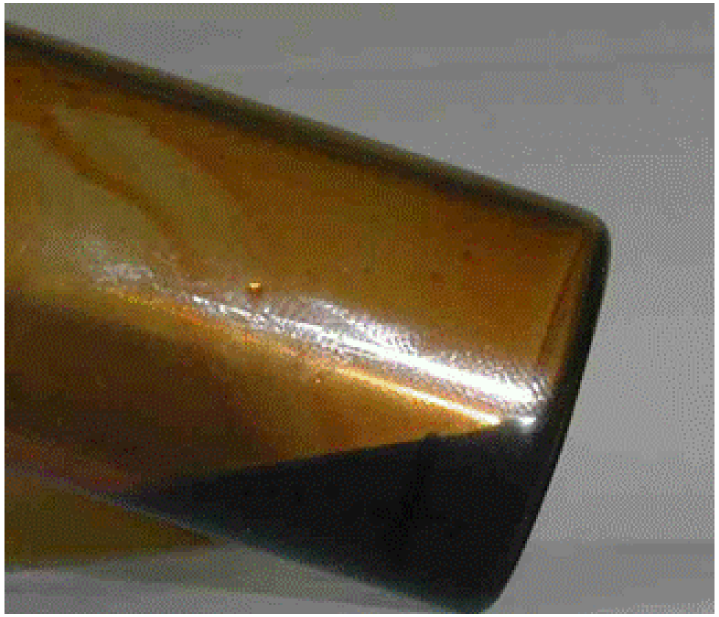
The amount of surfactant present in the system before and after two washings was 28.41and 15.47% respectively.



•Strength of surfactant binding

* G. G.Prakash, J Philip, T. J.Kumar &B. Raj *J. Phys. Chem. B* 2007, *111*, 7978

Ferrofluid



- **Unusual properties**

A unique material that has both magnetic and liquid properties

Ability to conform to any geometry

(The location of the fluid can be precisely controlled)

Viscosity, Apparent density, Birefringence

Nano-particle Size restrictions

- **Stability in magnetic field gradient**

$$\frac{kT}{\mu_0 MHV} \geq 1 \quad ; \qquad d \leq (6kT/\pi\mu_0 MH)^{1/3}$$

- **Stability against magnetic agglomeration**

Thermal/dipole-dipole contact energy = $24kT/\mu_0 M^2V \geq 1$;

$d \leq (144kT/\pi\mu_0 M^2)^{1/3}$

- **Stability against settling in a gravitational field**

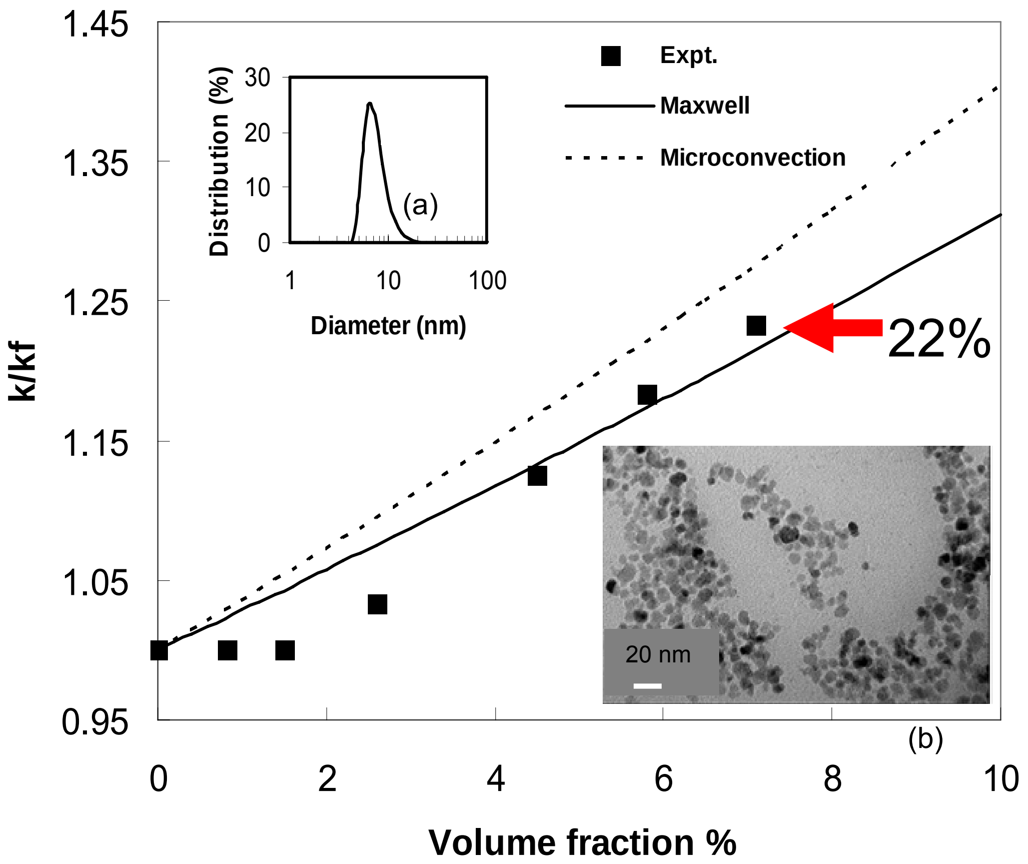
$$\frac{\Delta \rho g L}{\mu_0 M H} \approx 0.047 \qquad \Delta\rho = \rho_{solid} - \rho_{fluid}$$

H= 1000 G; M=5600 G; T=298K ; **d < 15 nm**

Nanofluid used

- Fe_3O_4 nanoparticles : ~7 nm
- Surfactant coating: Oleic acid/ Tetramethyl ammonium hydroxide (TMAOH)
- Coating thickness: ~ 1.5 nm
- Carrier Fluid: Organic /water

k vs Volume fraction



- 7.08 vol.% gives an enhancement in thermal conductivity of 22%.

- Maxwell model shows reasonably good agreement, especially at higher volume fractions.

$$\frac{k}{k_f} = \frac{1+2\beta\phi}{1-\beta\phi}$$

$$\beta = \frac{(k_p - k_f)}{(k_p + 2k_f)}$$

$k_f = k_f + \alpha k_p$

$$\alpha = \frac{2R_b k_f}{d}$$

J.Philip, Shima, Baldev Raj. Appl. Phys. Letts. 2007

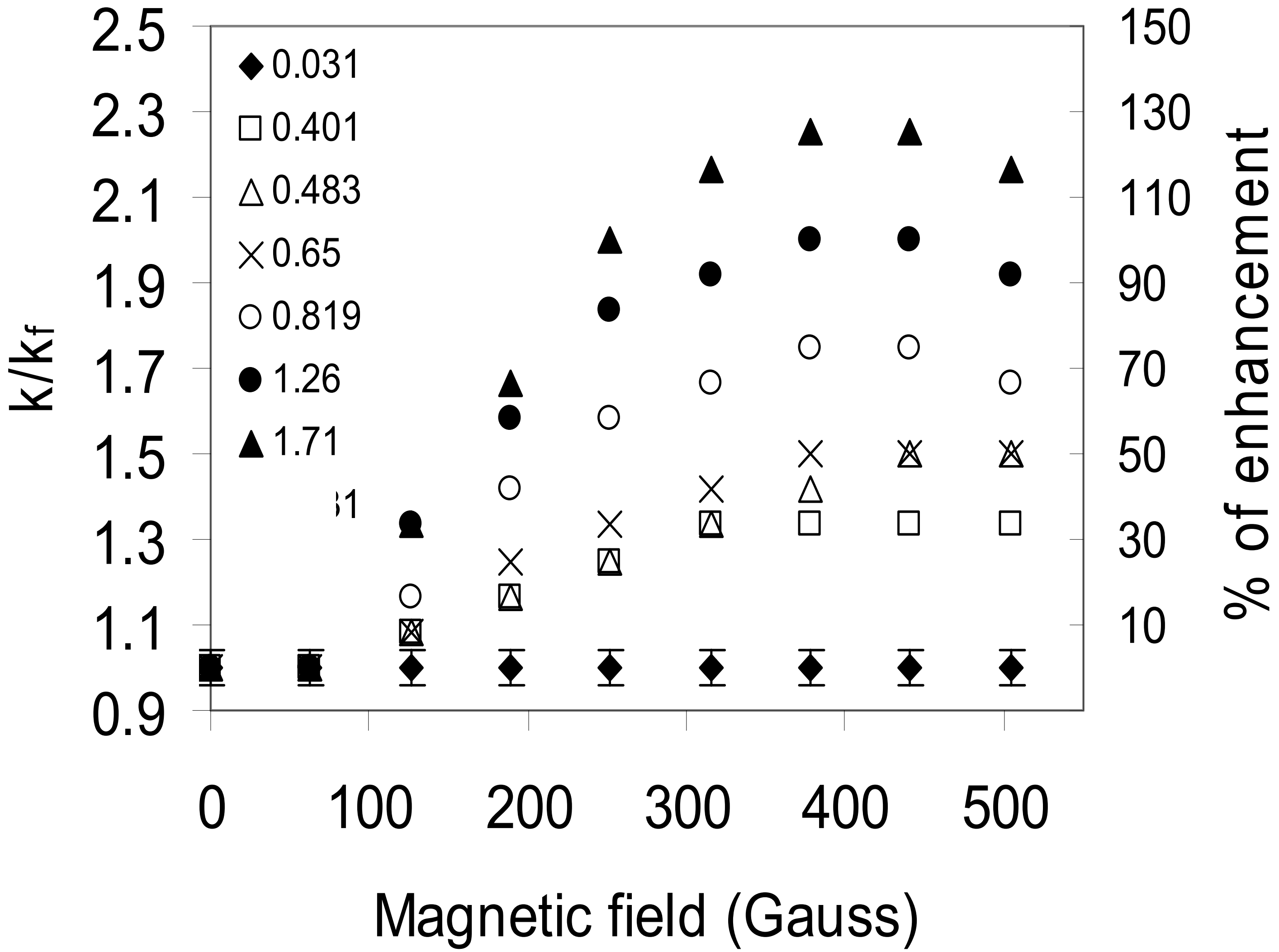
J.Eapen.. Z.Yip, Phys. Rev. Lett. **2007**, 99**,** 095901 (silica nanoparticles)

Microconvection model *(R.Prasher…Phys. Rev. Lett*. **2005**, 94, 025901)

$$\frac{k}{k_f} = (1 + A\,\mathrm{Re}^{\gamma}\,\mathrm{Pr}^{0.333}\,\varphi)\left(\frac{1+2\beta\phi}{1-\beta\phi}\right)$$

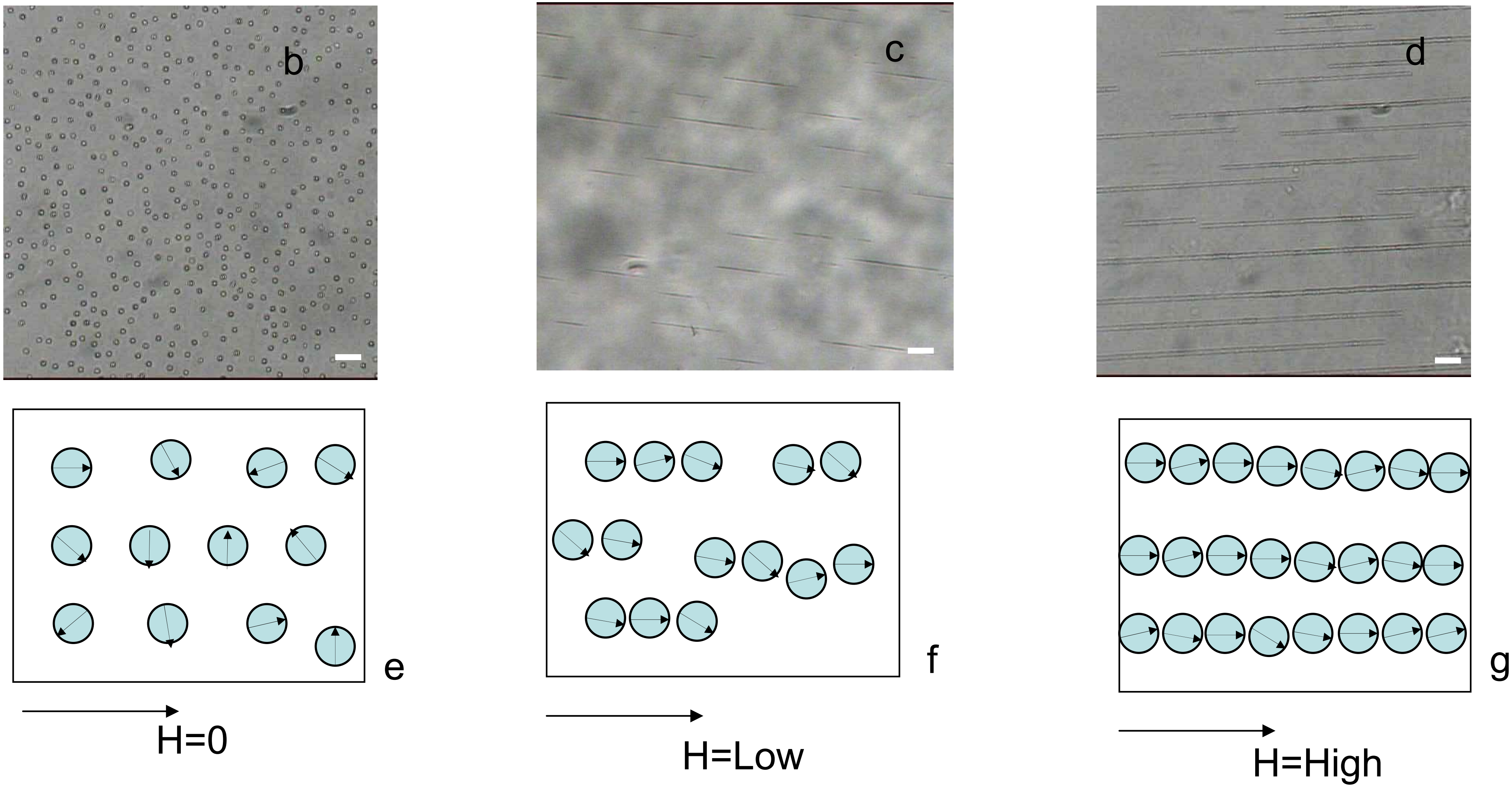
A is a constant, Re and Pr and the Reynolds and Prandlt number nanoparticles and base fluid respectively, γ is a system dependent exponent.

Thermal conductivity under magnetic field in Fe_3O_4 suspensions

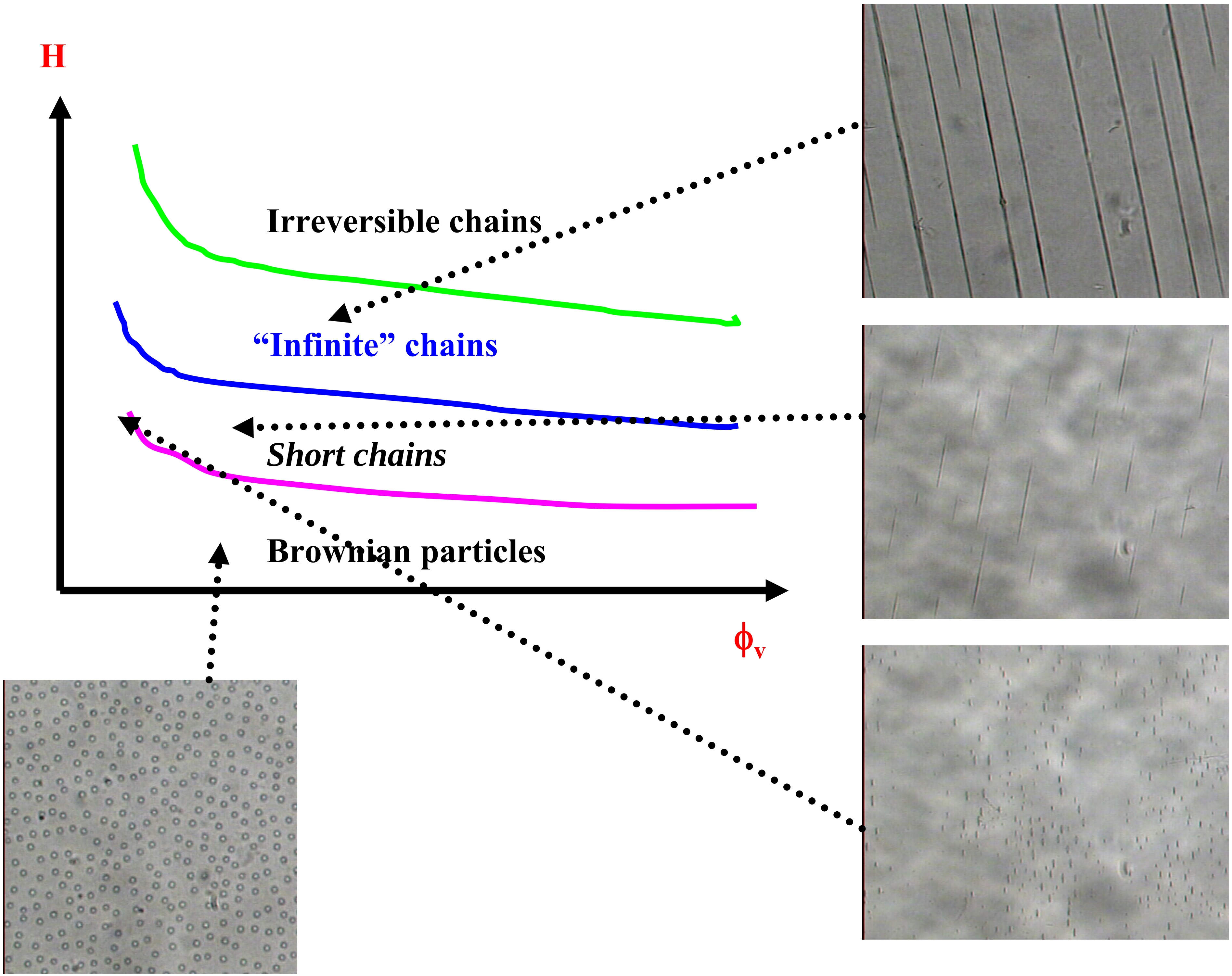


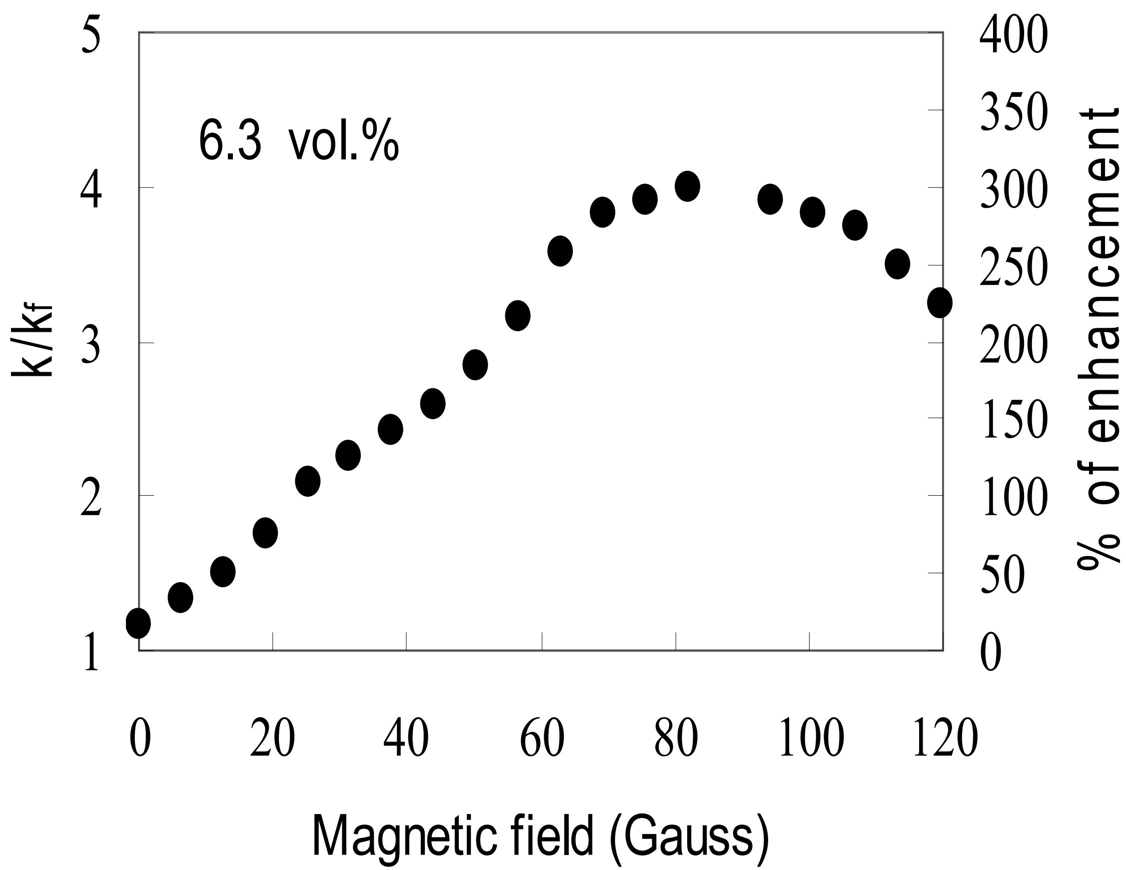
J.Philip, Shima, Baldev Raj. Appl. Phys. Letts. 2007

What happens when field is applied?



When the dipolar interaction energy becomes sufficiently strong, the magnetic particles form chain like structure.


H
Irreversible chains
"Infinite" chains
Short chains
Brownian particles
ϕ_v

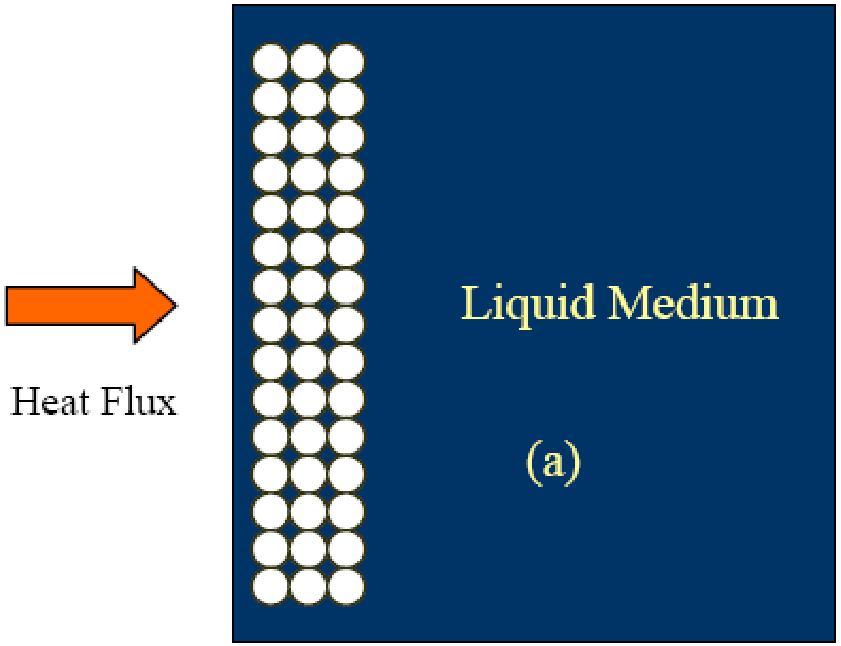


The interparticle dipole-dipole interaction between the magnetic particles is

$$U_d(ij) = -\left[3\frac{(m_i.r_{ij})(m_j.r_{ij})}{r_{ij}^5} - \frac{(m_i.m_j)}{r_{ij}^3}\right] \quad r_{ij} = r_i - r_j$$

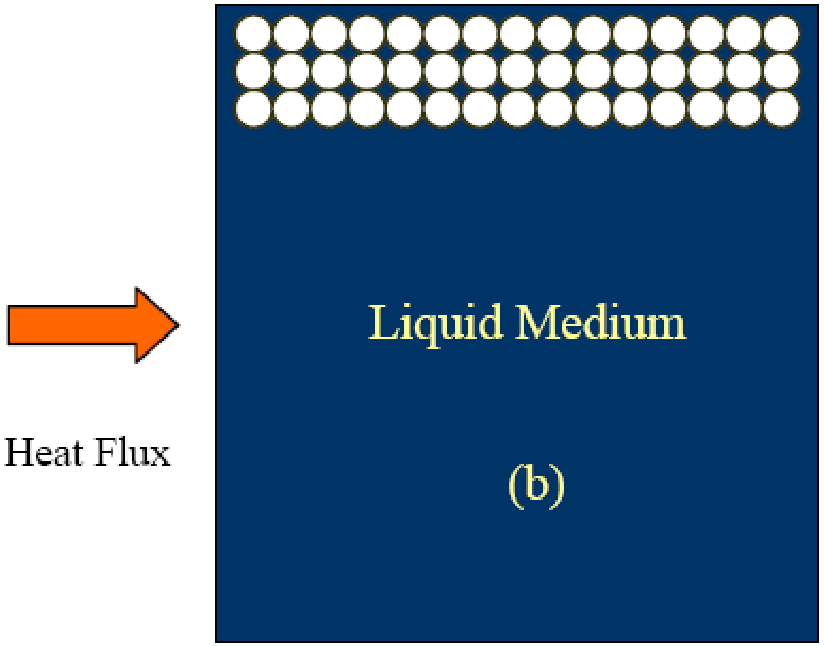
J Philip , Shima, Baldev Raj, Appl. Phys. Letts, 91 (2007) 203108

Mean-Field Models



Modes of conduction:
base fluid and np
- Series
- Parallel modes

- In reality, these possibilities are not strictly possible.



$$\frac{1}{\kappa^{=}} = \frac{(1-\phi)}{\kappa_f} + \frac{\phi}{\kappa_p}$$

$$\kappa^{\parallel} = (1-\phi)\kappa_f + \phi\kappa_p$$

[Hashin Z and Shtrikman S, J. 1962 *App. Phys.* **33** 3125.]

$$k_f\left[1+\frac{3\phi[k]}{3k_f+(1-\phi)\kappa}\right]\le k\le\left[1-\frac{3(1-\phi)[k]}{3k_p-\phi[k]}\right]k_p$$

In the limit (ϕkp/kf)>>1, the predicted values of k/kf for

Upper HS → (2ϕ/3)kp/kf ~ 245 %

Parallel modes → ϕkp/kf ~ 367%

Observed enhancement ~ 300%

Upper HS limit: Conduction path is through dispersed particles.

Lower HS limit: NPs are well suspended and conduction is through series modes

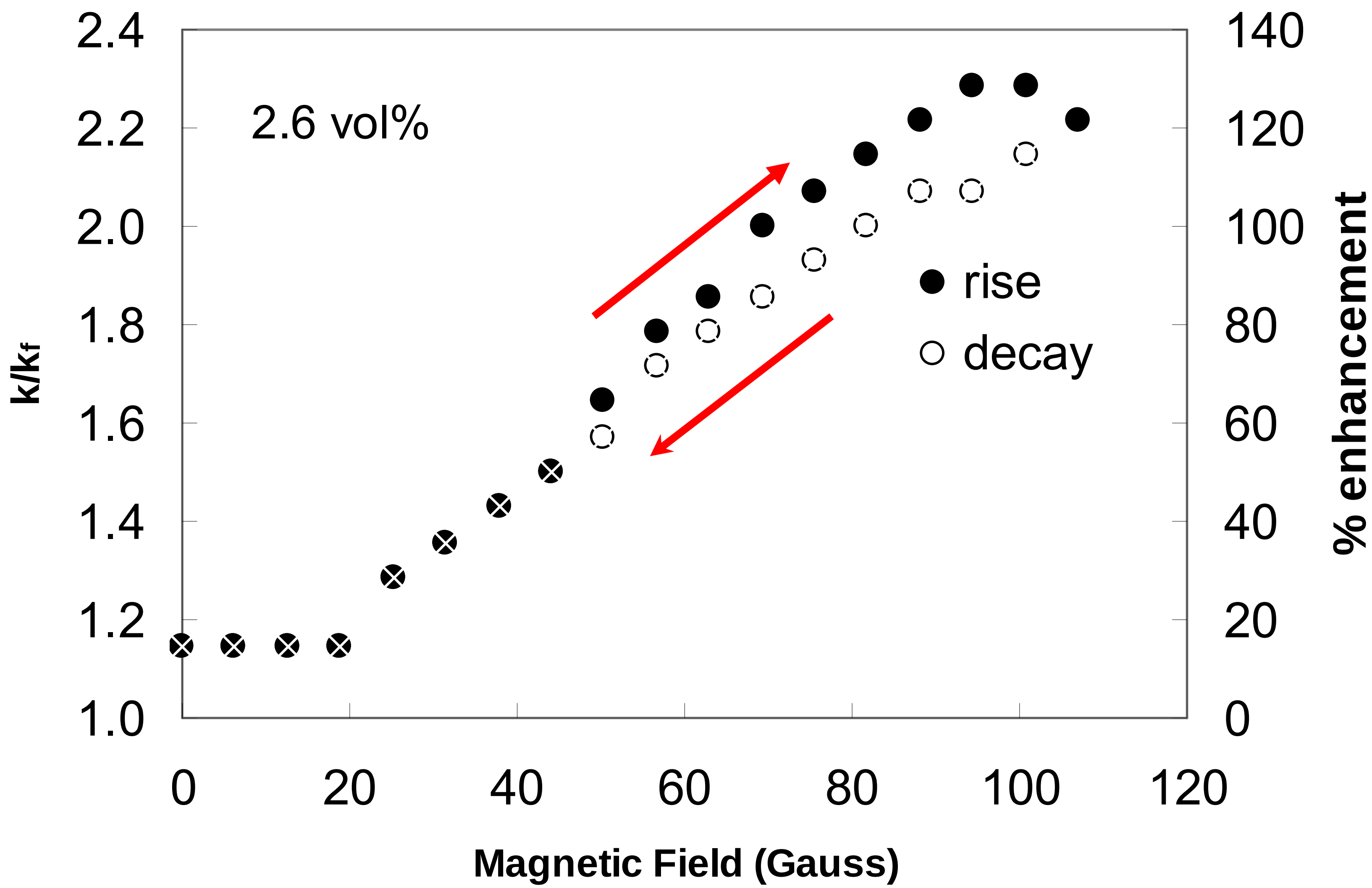
Convection vs. Percoalation

The convection velocity v drops drastically with particle size.

$$v = \sqrt{\frac{18 k_B T}{\pi \rho d^3}}$$

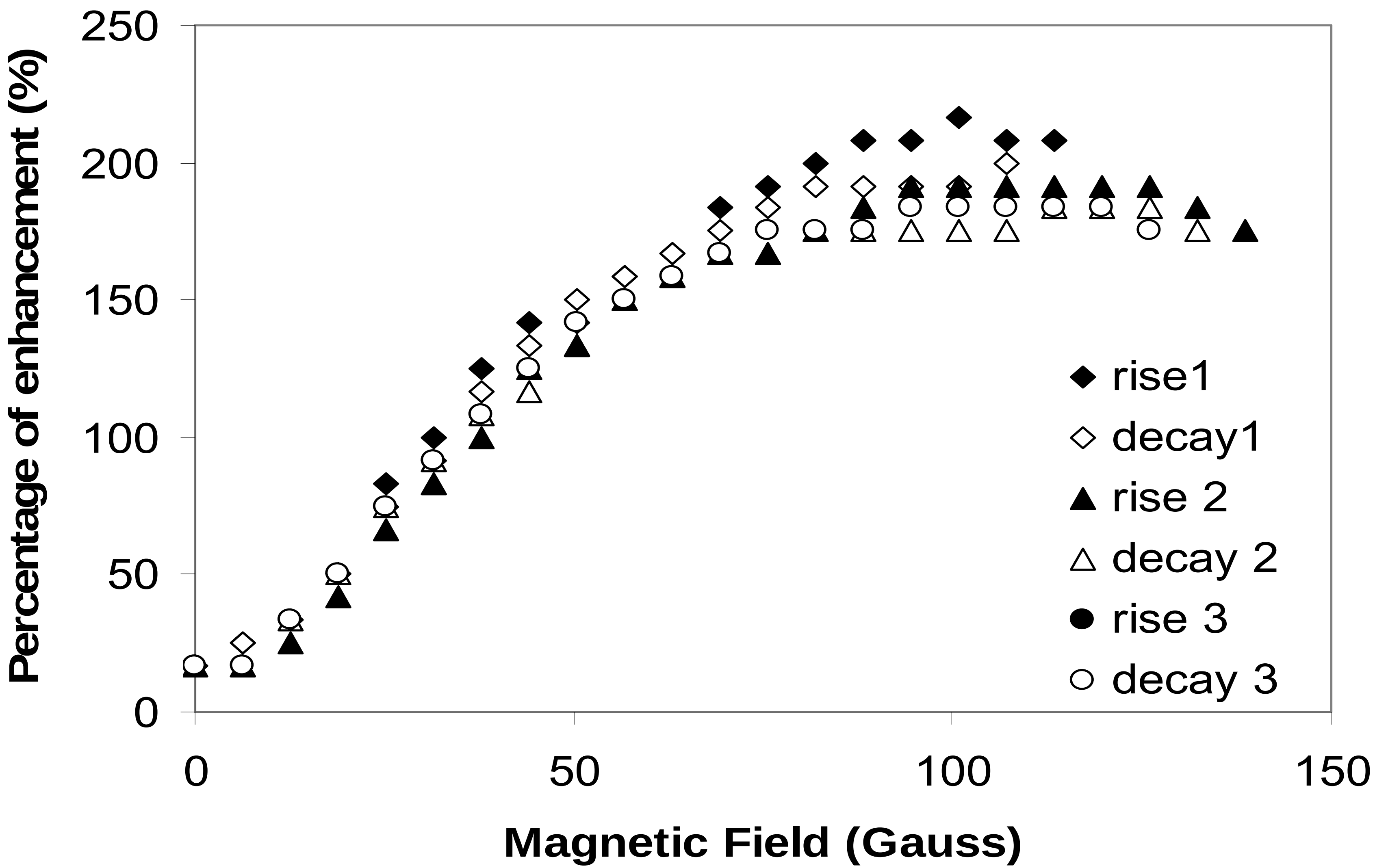
Thermal conduction through percolating nanoparticle paths in nanofluids

Reversibility



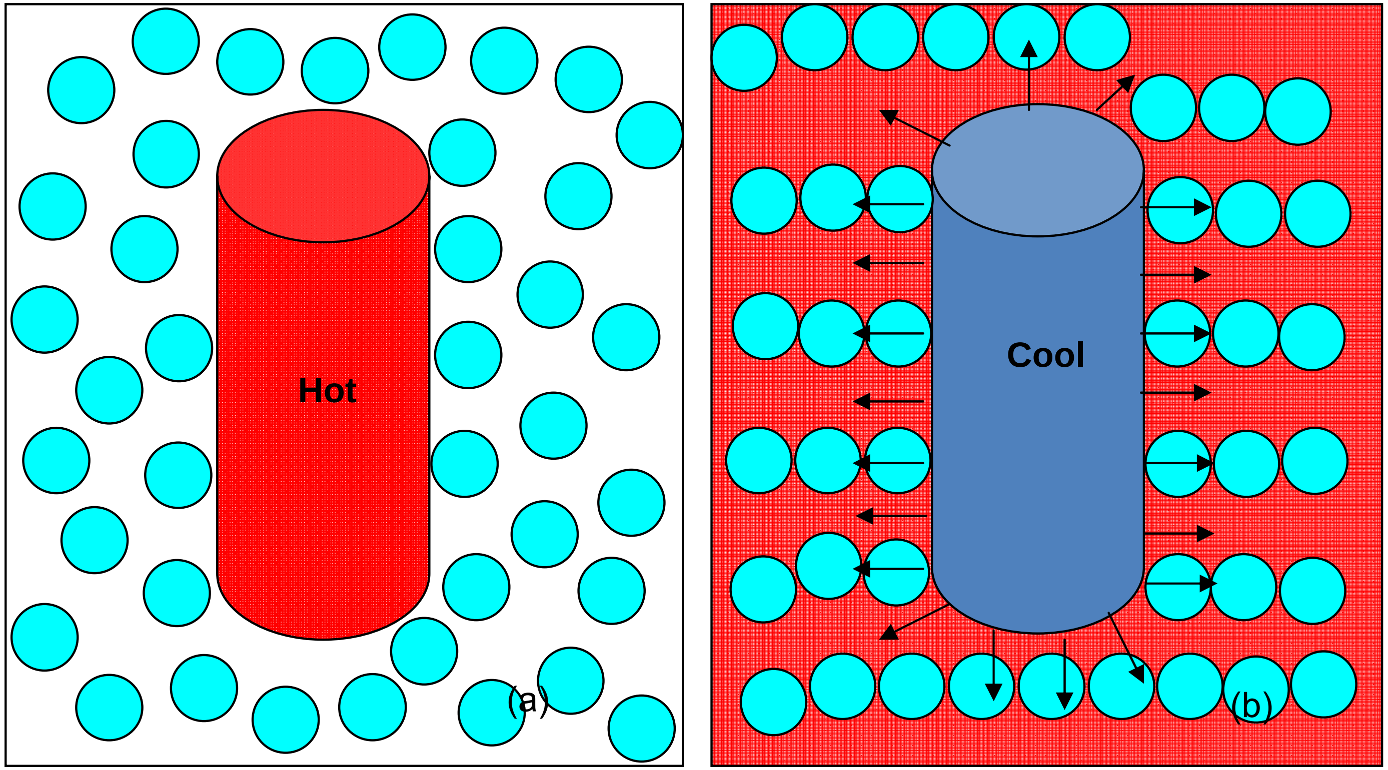
J Philip , Shima, Baldev Raj, Appl. Phys. Letts, 92(4) 2008

Cycle

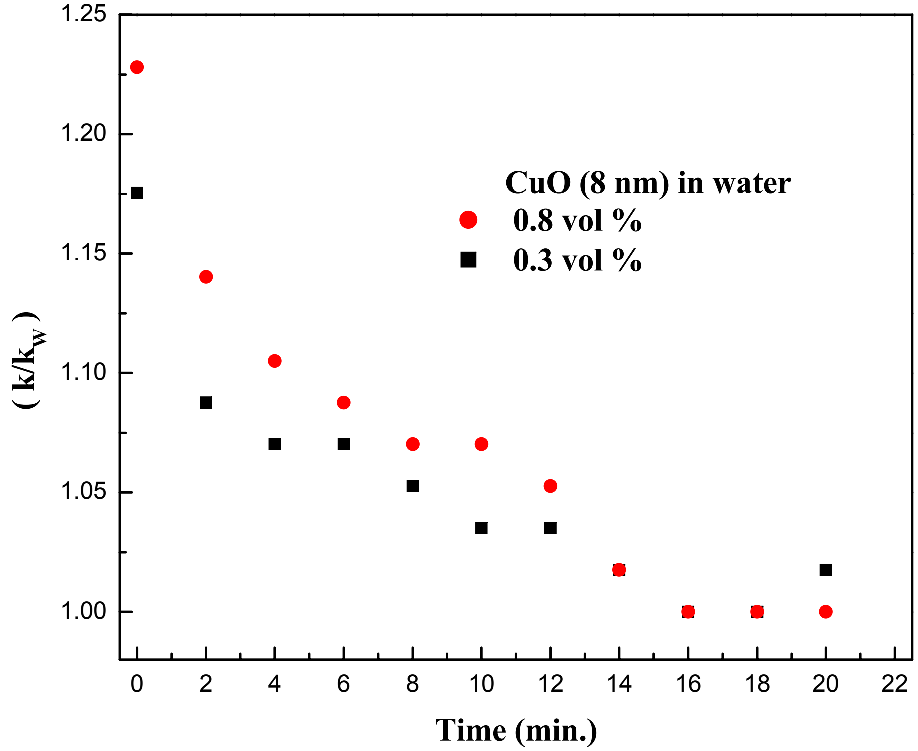


J Philip , Shima, Baldev Raj, Appl. Phys. Letts, 92(4) 2008

Applications



CuO nanoparticles



~30 % enhancement with 1 % vol. of CuO

Karthekeyan, J. Philip & B. Raj; **Mat. Chem. and Phys. 109 (2008) pp 50–55**

International Nanofluid Properties Benchmark Exercise (INPBE) MIT, USA

Sample	% of enhancement
Sample1 (Al_2O_3 nanorods in water)	1.75
Sample 2 (Al_2O_3 Nanoparticles in oil) Low concentration	6.67
Sample 3 (Al_2O_3 Nanoparticles in oil) High concentration	13.33
Sample 4 (Al_2O_3 Nanorods in oil) Low concentration	6.67
Sample 5 (Al_2O_3 nanorods in oil) High concentration	20.00

Conclusions

- Direct evidence for efficient transport of heat through percolating paths.
- In stable nanofluids, the enhancement was within the Maxwell's limit of 3ϕ
- Well-dispersed nanoparticles suspensions (without aggregates) do not exhibit significant enhancement of thermal conductivity.

Cont…..

Conclusions

- For magnetite nanofluid, the maximum enhancement in the thermal conductivity observed is 300% (k/k_f =4.0) at a particle loading of 6.3 vol.%, under the influence of an applied magnetic field of 80 G.
- The maximum enhancement under magnetic field is about 48ϕ (~ parallel mode of conduction)

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- Ayyappan
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Ph.D students

Thank You