Rayleigh-Bernard Convection in Nanofluids

Dr. SUDHAKAR SUBUDHI

Indian Institute of Technology Roorkee, Roorkee

Collaborator: Rajesh Choudhary

Outlines

- Introduction
- Preparation and Stability Analysis of Nanofluids
- Characterization of Nanofluids
- Experimental set up
- Experimental Results
- Conclusions

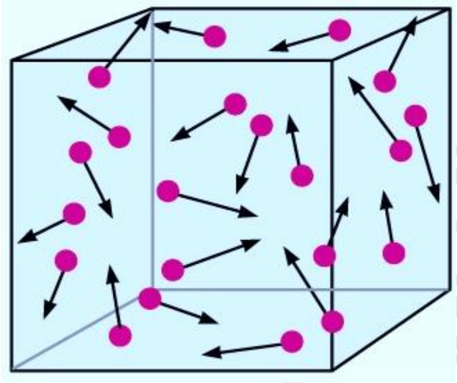
Introduction

- Invention: In 1995, SUS Choi, a scientist from Argonne National Laboratory
- Size: The nano particle size in the range of 1-100 nm.
- Important feature: Ability to adjust the thermal (thermal conductivity) and physical properties (size, shape, wettability) by changing parameters of nanofluid synthesis .
- Applications: Nuclear systems cooling, electronics cooling, microfluidic, nanofluidic, drug delivery, solar water application and so on.

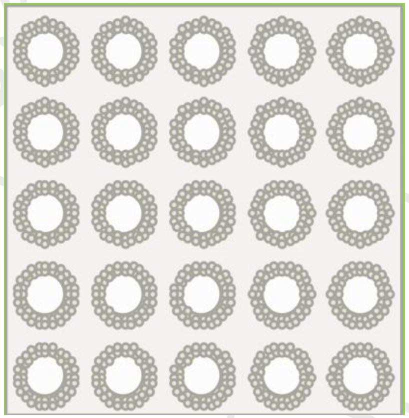
Heat transfer mechanism in Nanofluids

Brownian Motion- In nanofluids the nanoparticles are always in random motion called Brownian motion and additional energy transport is possible due to this motion.

Interfacial Layer- The ordered nanolayer act like a thermal bridge between solid particle and liquid and result in appreciable increased heat transfer.



Brownian motion



Interfacial layer

Intensification of turbulence- It is due to presence of small solid nano particles

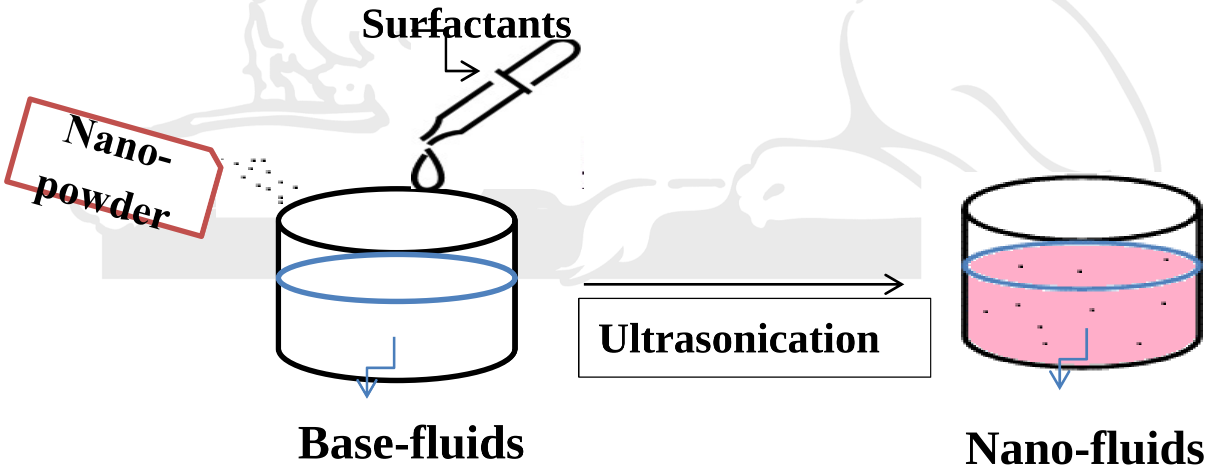
Synthesis of Nanofluids

Nanofluids

- The one-step method: By dispersing metallic nanoparticles directly in the base fluid by using physical vapour deposition or liquid-chemical method
- The two-step method:

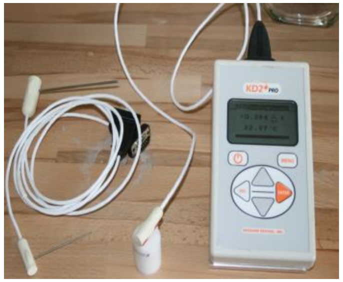
Nanoparticles

- Physical methods (Grinding methods, Inert Gas Condensation)
- Chemical methods (Chemical Vapour Deposition, Chemical precipitation, Micro-emulsions, spray pyrolysis, thermal spraying etc.)



Characterization of nanofluids

Thermal Conductivity Measurement



KD2 Pro, Decagon Devices, USA

Hot Disk Thermal Property Analyzer, Swedan

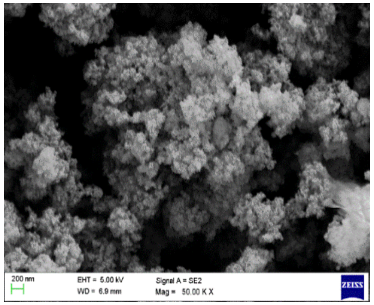
Viscosity Measurement

MCR-102, Anton Paar, Austria

Stability Analysis

Zetasizer, Malvern, UK

Scanning Electron Microscope (SEM) Analysis

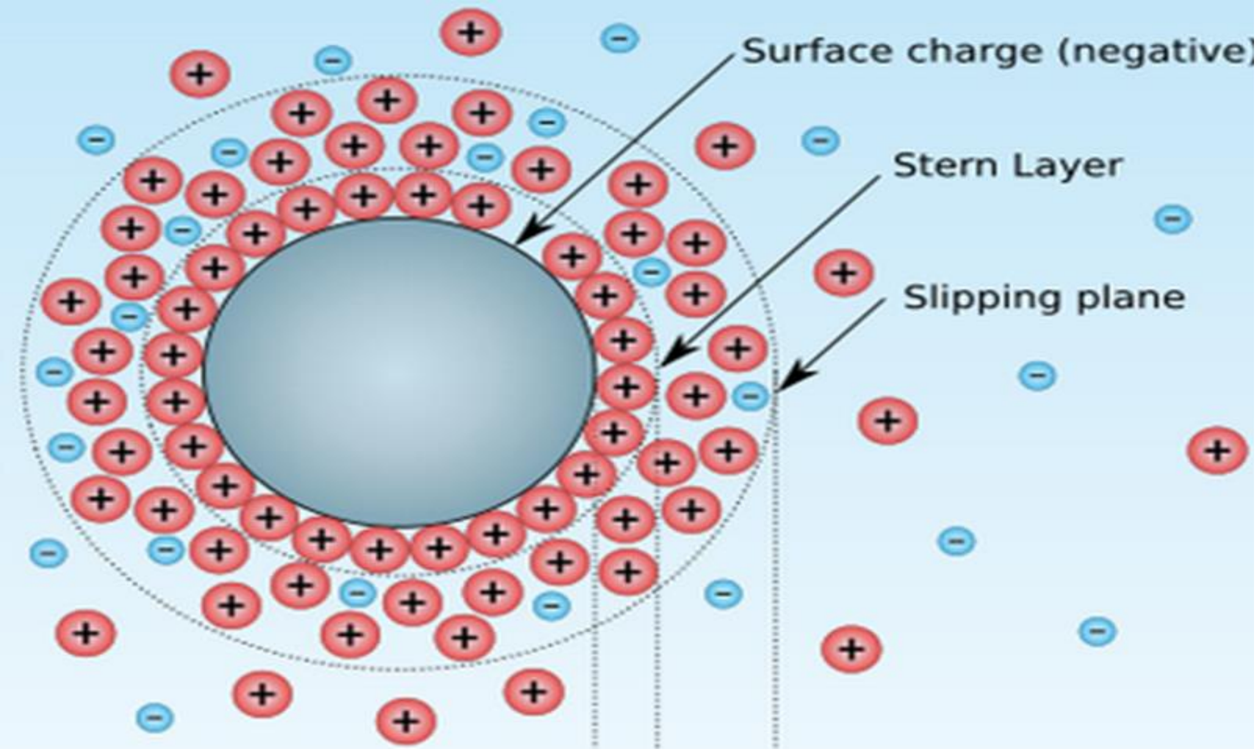


Al_2O_3 -20 nm
(Actual 20.49 nm)

Subudhi et. al, NANO, Vol.11, 2016

Zeta Potential

Zeta potential is the potential difference between the dispersion medium and the stationary layer of fluid attached to the dispersed particle.



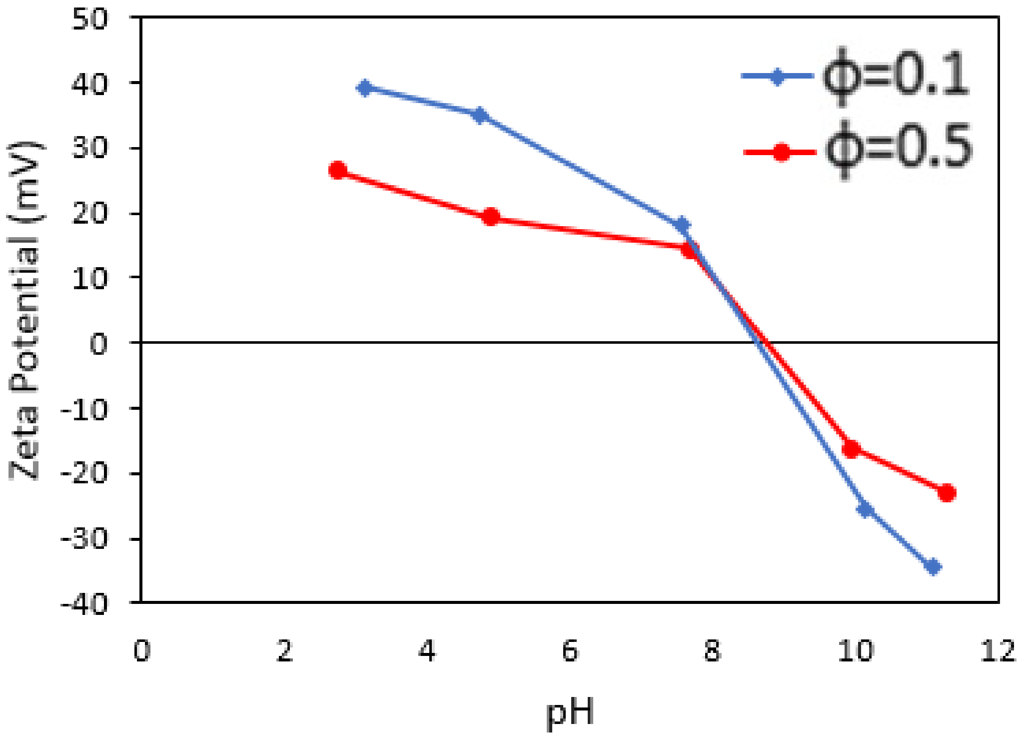
Stability of nanofluids

- **Using pH Control-** Increases the stability due to strong repulsive forces

- **Addition of surfactant-** Lowers the surface tension of liquids and hence increases the surpension time of particles

- **Ultrasonication-** Breaks down the agglomeration of the particles and disperse the nanoparticles uniformly in base fluid.

Effect of pH



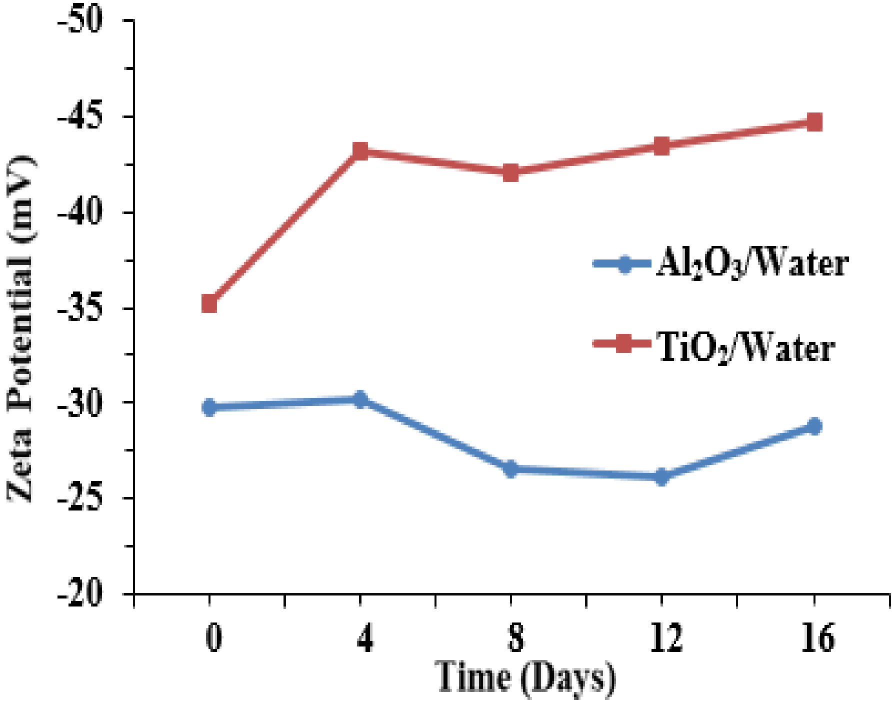
Zeta potential Variation with the pH for Al_2O_3/Water Nanofluid at a Sonication time of 120 minutes (Additives-HCl/NaOH)

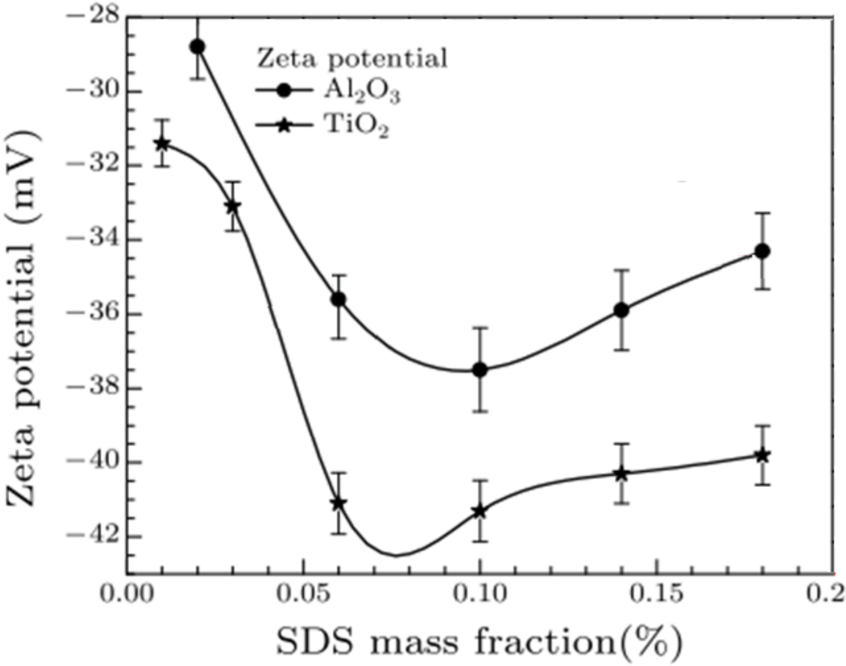
- At low concentration the Zeta potential is high while at high concentration zeta is less because with rise in concentration agglomeration and size of particles increases and hence zeta decreases.

Subudhi et. al., “Stability analysis of Al_2O_3/water nanofluids”, Journal of experimental Nanoscience, DOI: 10.1080/17458080.2017.1285445, 2017

Effect of surfactant

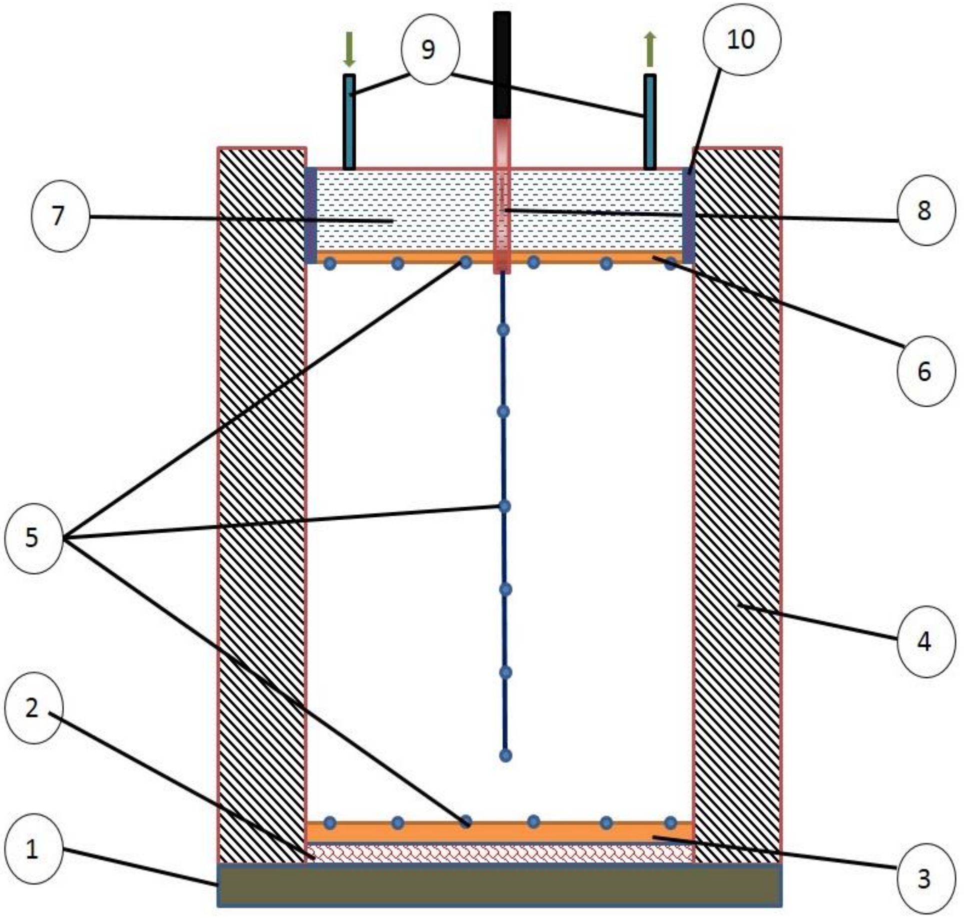
- Zeta potential remains almost constant, when sodium dodecyl sulfate (SDS) surfactant is added because there is no agglomeration due to reduction in surface tension.





W. Xian-Ju, L. Hai, L. Xin-Fang, W. Zhou-Fei, L. Fang, Stability of TiO_2 *and* Al_2O_3 *Nanofluids, Chinese Physics Letters 28 (8) (2011) 086601-4.*

Experimental set up



- Schematic diagram of test section: 1. Wooden block, 2. Heater, 3. Heating surface, 4. Insulation, 5. Thermocouples, 6.Cooling surface, 7. Cooling chamber, 8. Rubber pipe, 9. Cooling water inlet & outlet, and 10. Gasket

Thermo-physical properties of the Al_2O_3/DW nanofluids

- The mixing theory was used to measure the density of the nanofluid, given by following Eq.

$$\rho_{nf} = (1-\phi)\rho_f + \phi\rho_p$$

Khanafer and Vafai (2003) correlations for thermal expansion coefficient and heat capacity

$$\beta_{nf} = \frac{(1-\phi)(\rho\beta)_f + \phi(\rho\beta)_p}{\rho_{nf}}$$

$$C_{nf} = \frac{(1-\phi)(\rho C)_f + \phi(\rho C)_p}{\rho_{nf}}$$

Thermo-physical properties of the Al_2O_3/DW nanofluids

- Corcione (2011) correlations for dynamic viscosity and thermal conductivity

$$\frac{\mu_{nf}}{\mu_f} = \frac{1}{1 - 34.87\left(d_p/d_f\right)^{-0.3}\phi^{1.03}}$$

- Where d_f is the equivalent diameter of the base fluid molecule, given by

$$d_f = 0.1\left(\frac{6M}{N\pi\rho_f}\right)^{1/3}$$

$$\frac{k_{nf}}{k_f} = 1 + 4.4Re^{0.4}Pr^{0.66}\left(\frac{T}{T_{fr}}\right)^{10}\left(\frac{k_p}{k_f}\right)^{0.03}\phi^{0.66}$$

Configurations of nanofluids

- For the ease of understanding, all four configurations are designated as follows:
- NF-A: $\phi = 0.01$ vol. % and $d_p = 20$ nm
- NF-B: $\phi = 0.1$ vol. % and $d_p = 20$ nm
- NF-C: $\phi = 0.01$ vol. % and $d_p = 40$ nm
- NF-D: $\phi = 0.1$ vol. % and $d_p = 40$ nm
- From Pak and Cho (1998) relation:

$$\phi = \frac{1}{\frac{100}{m}\frac{\rho_{np}}{\rho_{bf}} + 1} \times 100\,\%$$

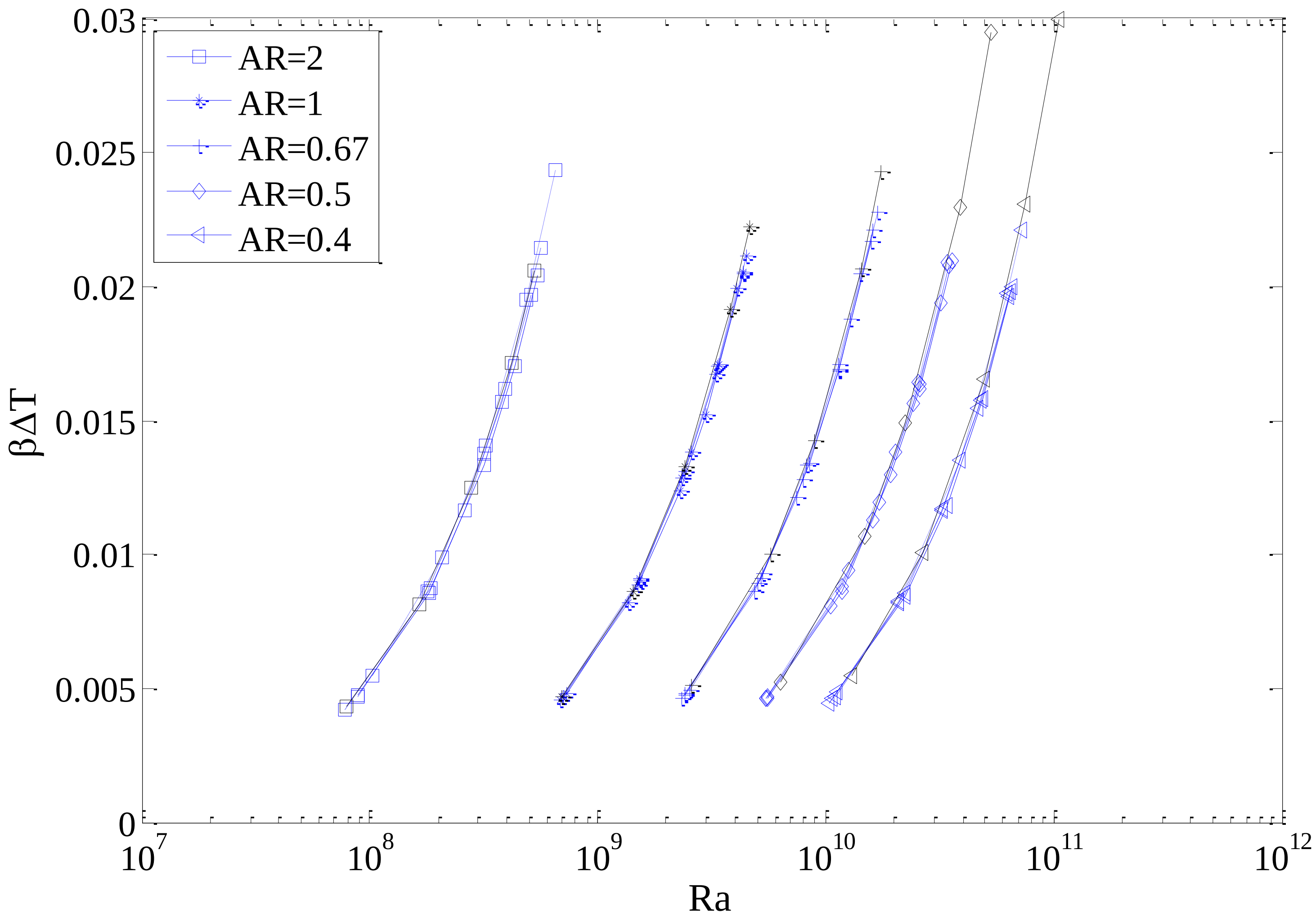
The range of various experimental parameters

Working Fluid	Ra × 10^{-7}	Nu	$\delta_T \times 10^3$ (m)	$\beta\Delta T \times 10^3$
DW	0.206 – 6609.6	6.71 – 252.21	3.43 – 0.519	0.5 – 22
Al_2O_3/DW (0.01 vol. %; 20 nm)	0.204 – 6383.7	6.79 – 252.34	3.49 – 0.596	0.6 – 23
Al_2O_3/DW (0.1 vol. %; 20 nm)	0.27 – 10520.0	5.1 – 178.06	3.53 – 0.63	0.7 – 24
Al_2O_3/DW (0.01 vol. %; 40 nm)	0.21 – 6418.3	6.67 – 249.19	5.01 – 0.61	0.4 – 21
Al_2O_3/DW (0.1 vol. %; 40 nm)	0.44 – 7203.8	8.86 – 207.95	4.01 – 0.69	0.8 – 27

Boussinesq Approximation

- For the validity of the Oberbeck-Boussinesq approximation, except the density, temperature dependence of the thermo-physical properties of water are anticipated constant.
- The several parameters are used to describe non-Oberbeck-Boussinesq (NOB) effects.
- One parameter is the relative change in density of the fluid which is given by $\beta\Delta T$.
- According to the Niemela and Sreenivasan (JFM,481), this should be less than 0.2 for validity of the Oberbeck-Boussinesq approximation.
- Another parameter is Busse's quantity (Q_b)*(Busse,JFM,30)* defined by

Boussinesq Approximation (cont.)



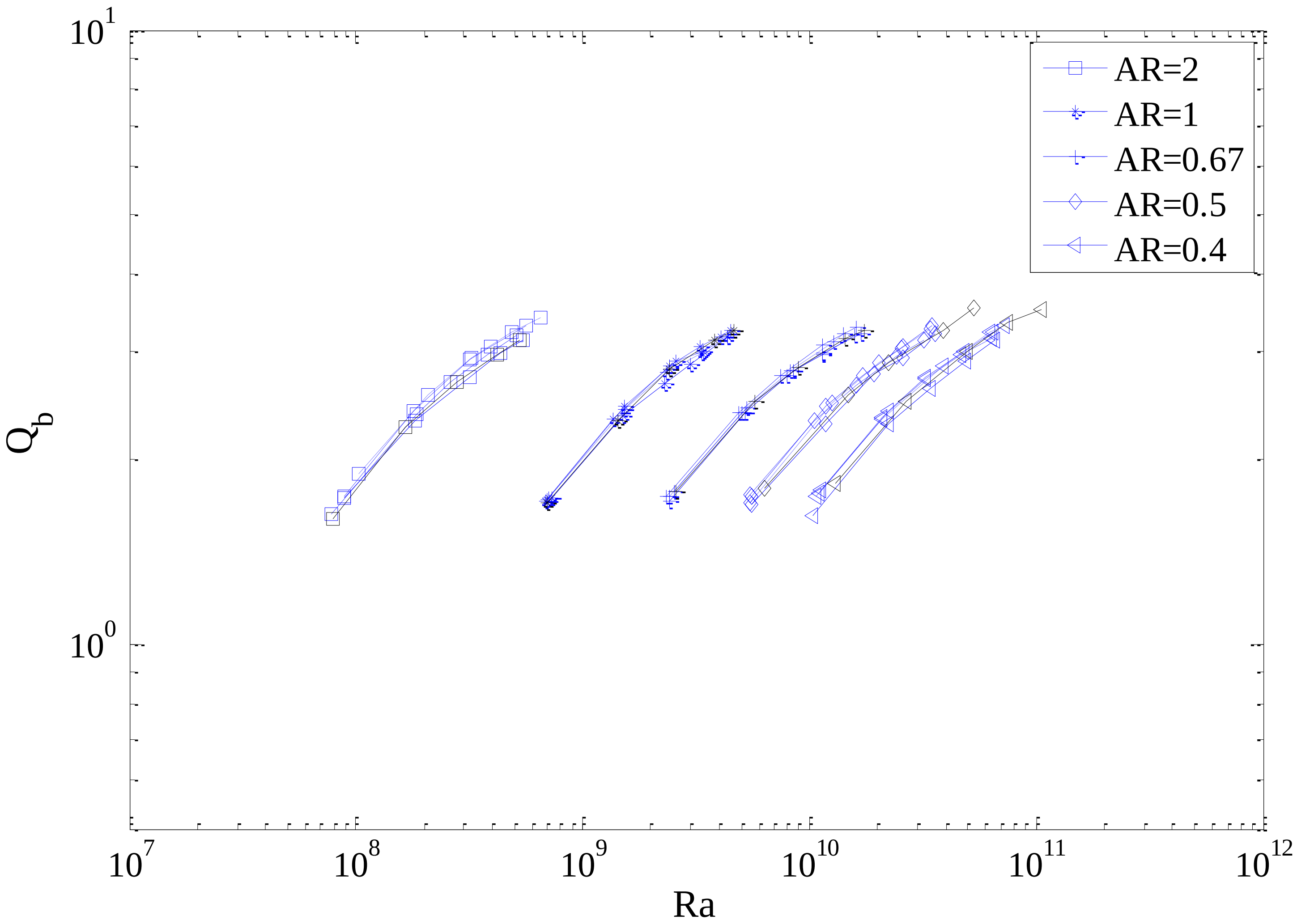
Boussinesq Approximation (cont.)

$$Q_b = \sum_{i=0}^{4} c_i P_i$$

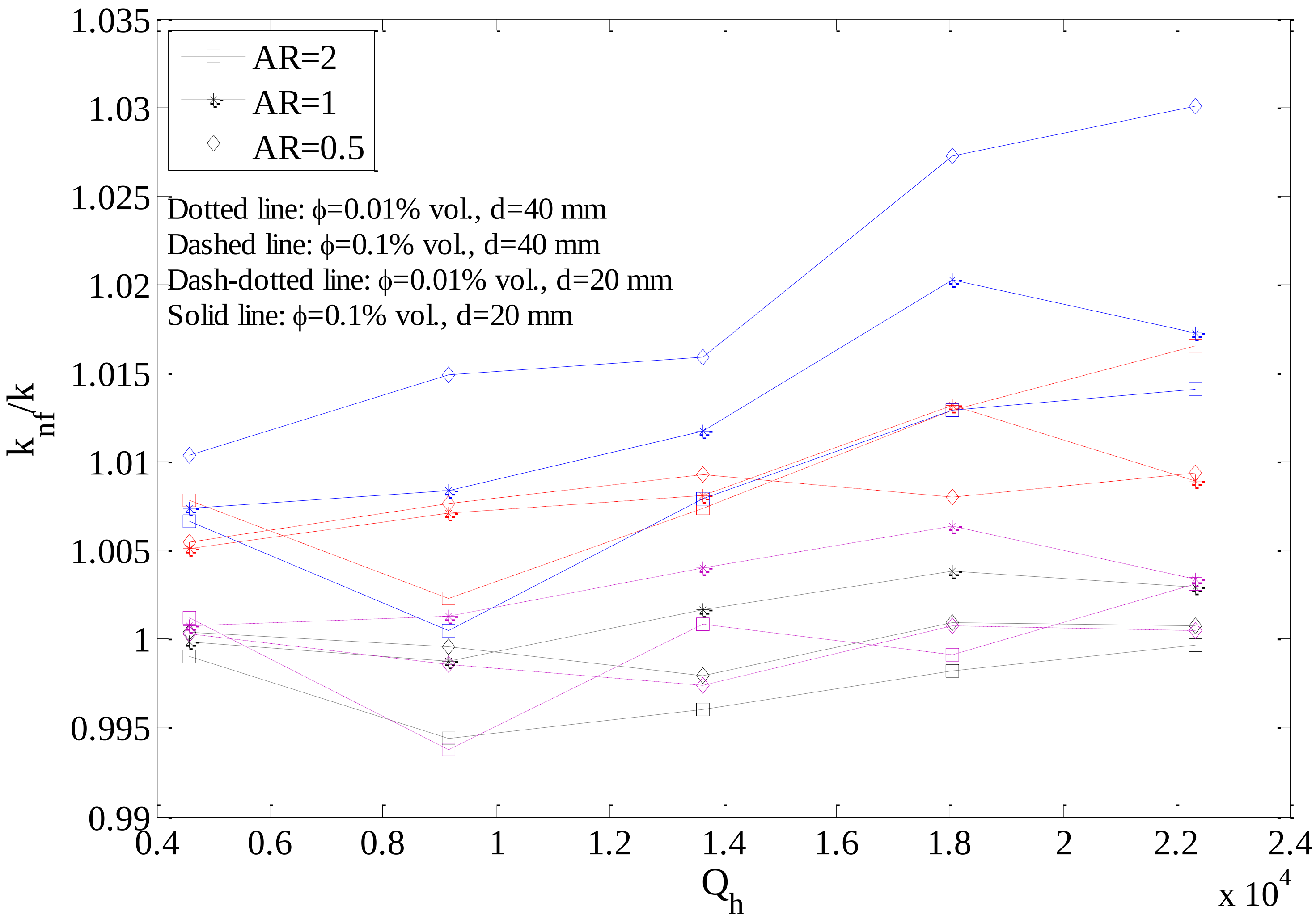
- Where P_i represents the fractional deviations of fluid properties:
- $P_0 = -\frac{\rho_b - \rho_w}{\rho_m}, P_1 = -\frac{\beta_b \rho_b - \beta_w \rho_w}{2\beta_m \rho_m}, P_2 = -\frac{\nu_b - \nu_w}{\nu_m}, P_3 = -\frac{\lambda_b - \lambda_w}{\lambda_m}, P_4 = -\frac{C_{pb} - C_{pw}}{C_{pm}}$
- The coefficients c_i depend on Prandtl number as follows:
- $c_0 = 2.676 - 0.361/\mathrm{Pr}, c_1 = -6.631 - 0.772/\mathrm{Pr}, c_2 = 2.765, c_3 = 9.540, c_4 = -6.225 + 0.386/\mathrm{Pr}$

- From figure , it is observed that these values are in the order of one and hence the Boussinesq approximation is valid (Niemela and Srinivasan, JFM, 481).

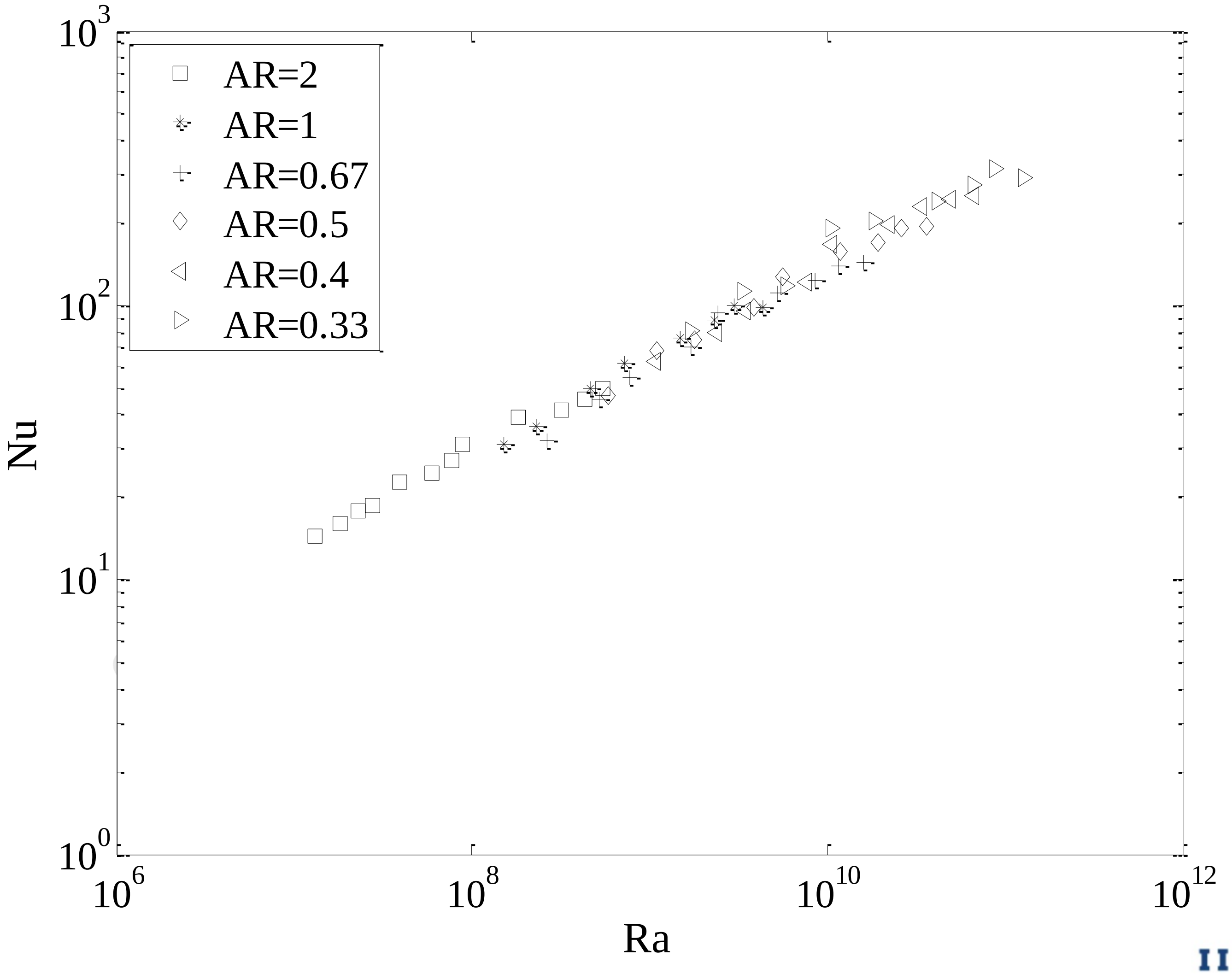
Boussinesq Approximation (cont.)



Thermal conductivity ratios

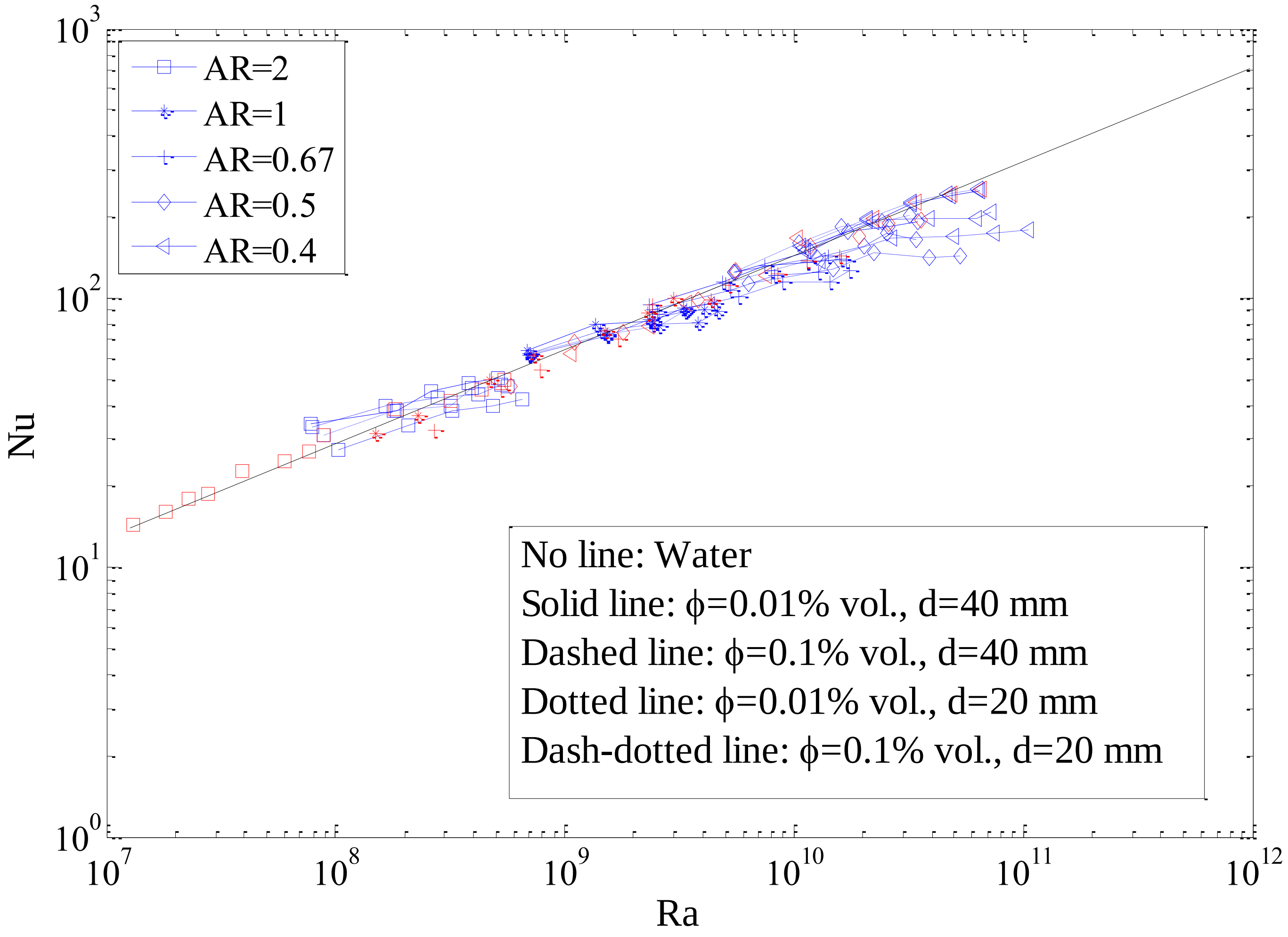


Nu-Ra plot for Water



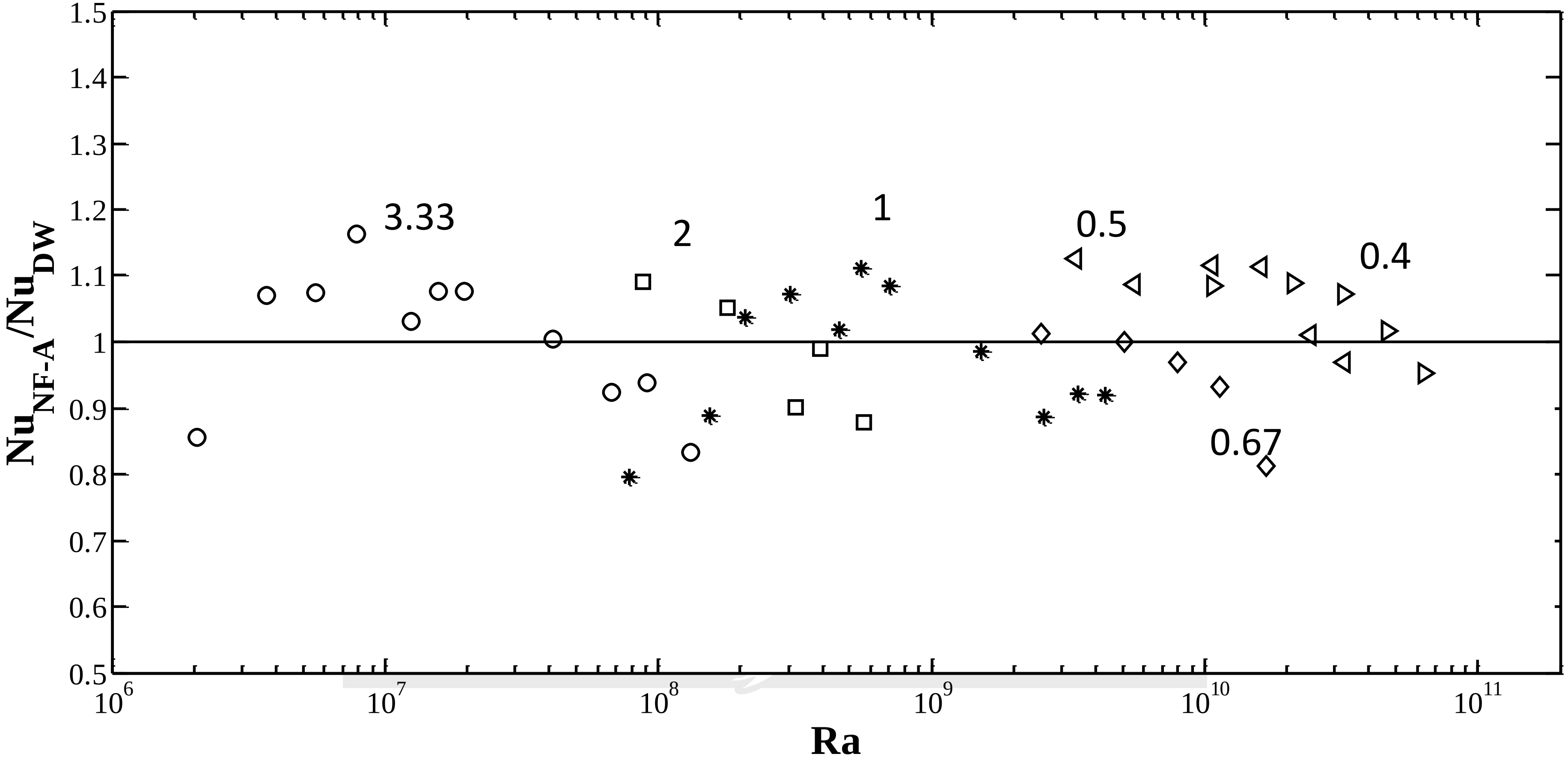
Nu-Ra plot for Nanofluids (ϕ=0.01,0.1% vol., d=40, 20 mm)

- No single line (Xia et. al. Phys. Fluids, 23)

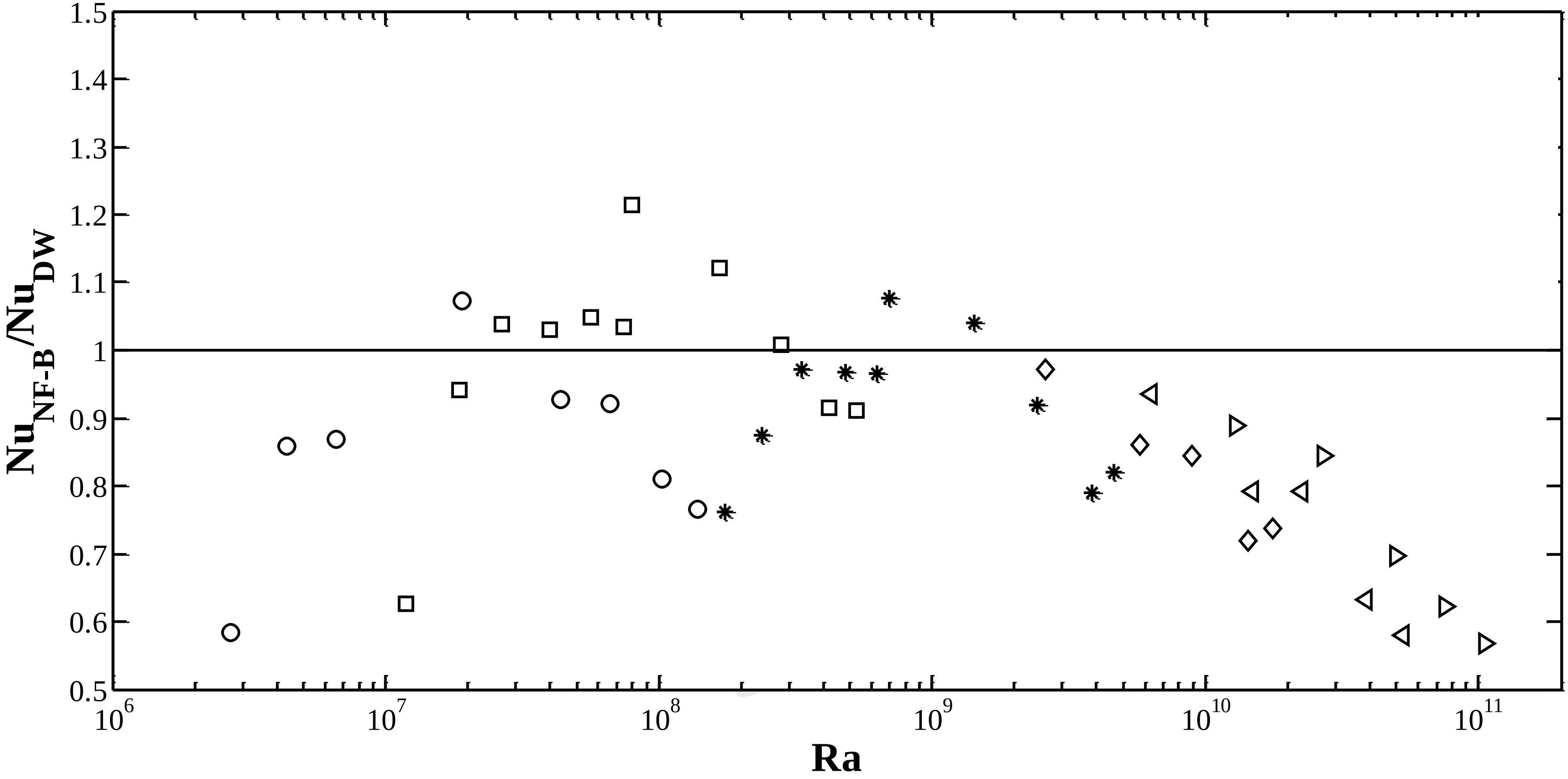


Rajesh Choudhary and Sudhakar Subudhi, Appl. Therm. Engg., 108, 2016

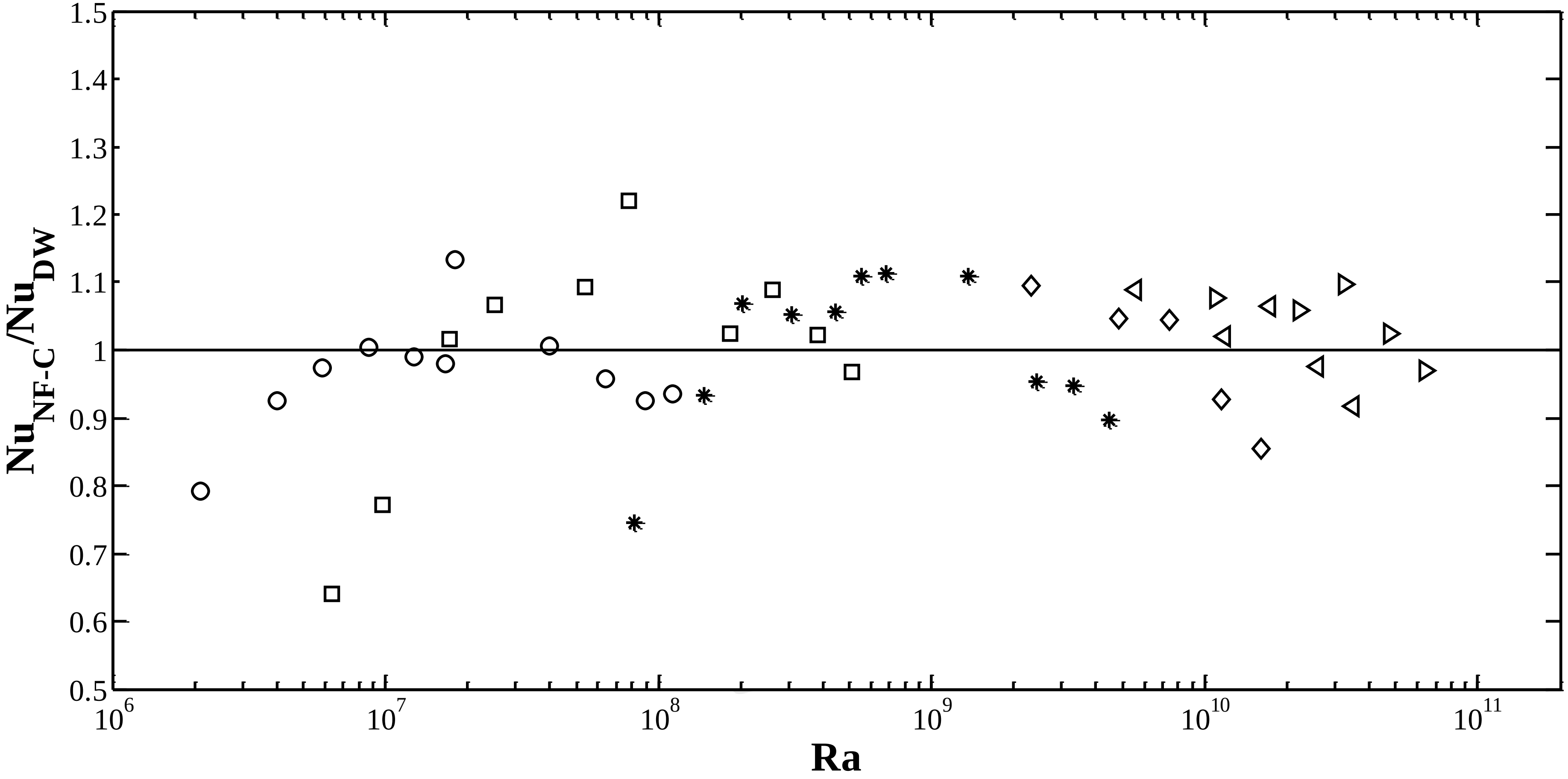
Nu-Ra plot for Nanofluids (ϕ=0.01% vol., d=20 mm)



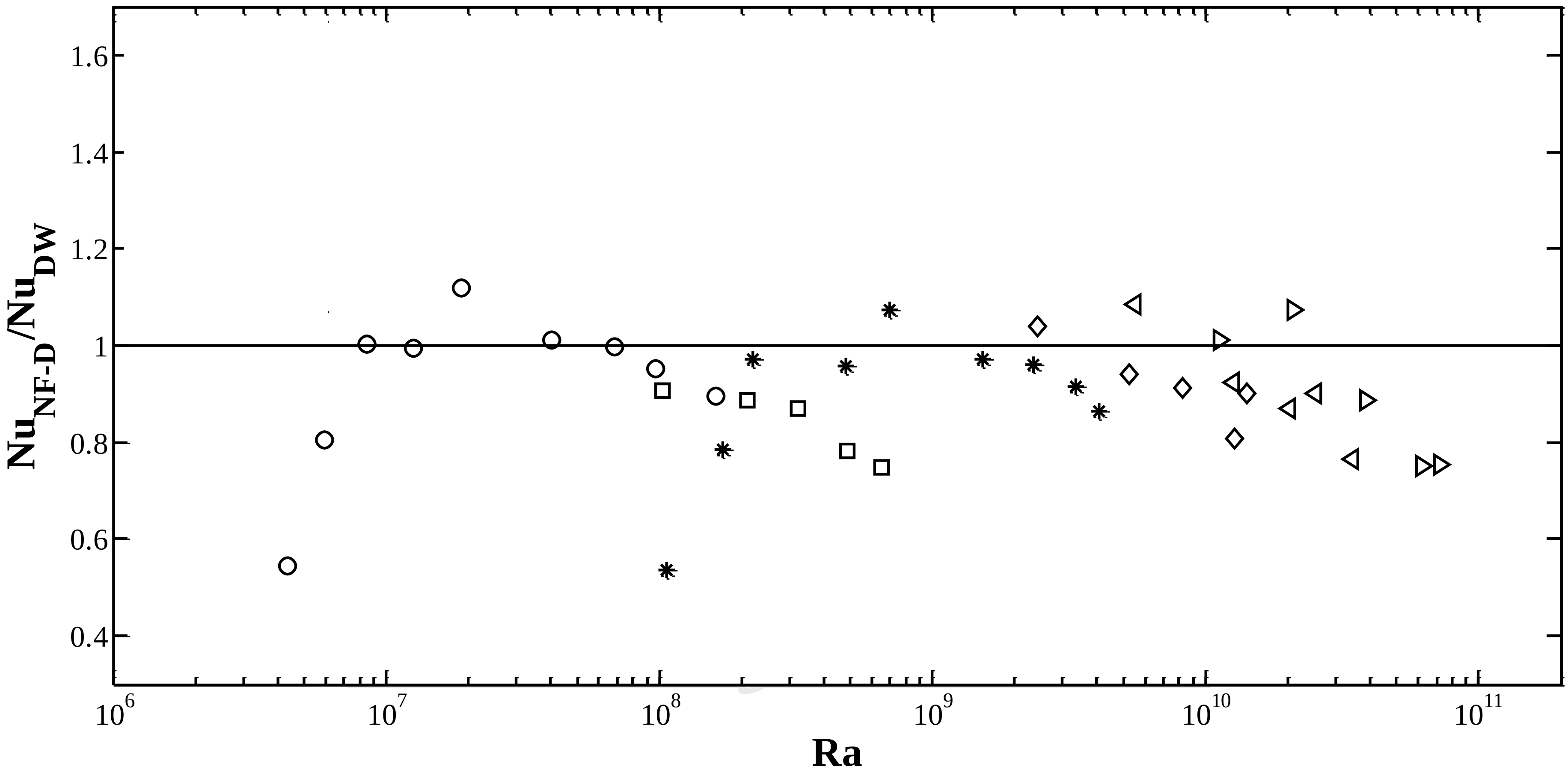
Nu-Ra plot for Nanofluids (ϕ=0.1% vol., d=20 mm)



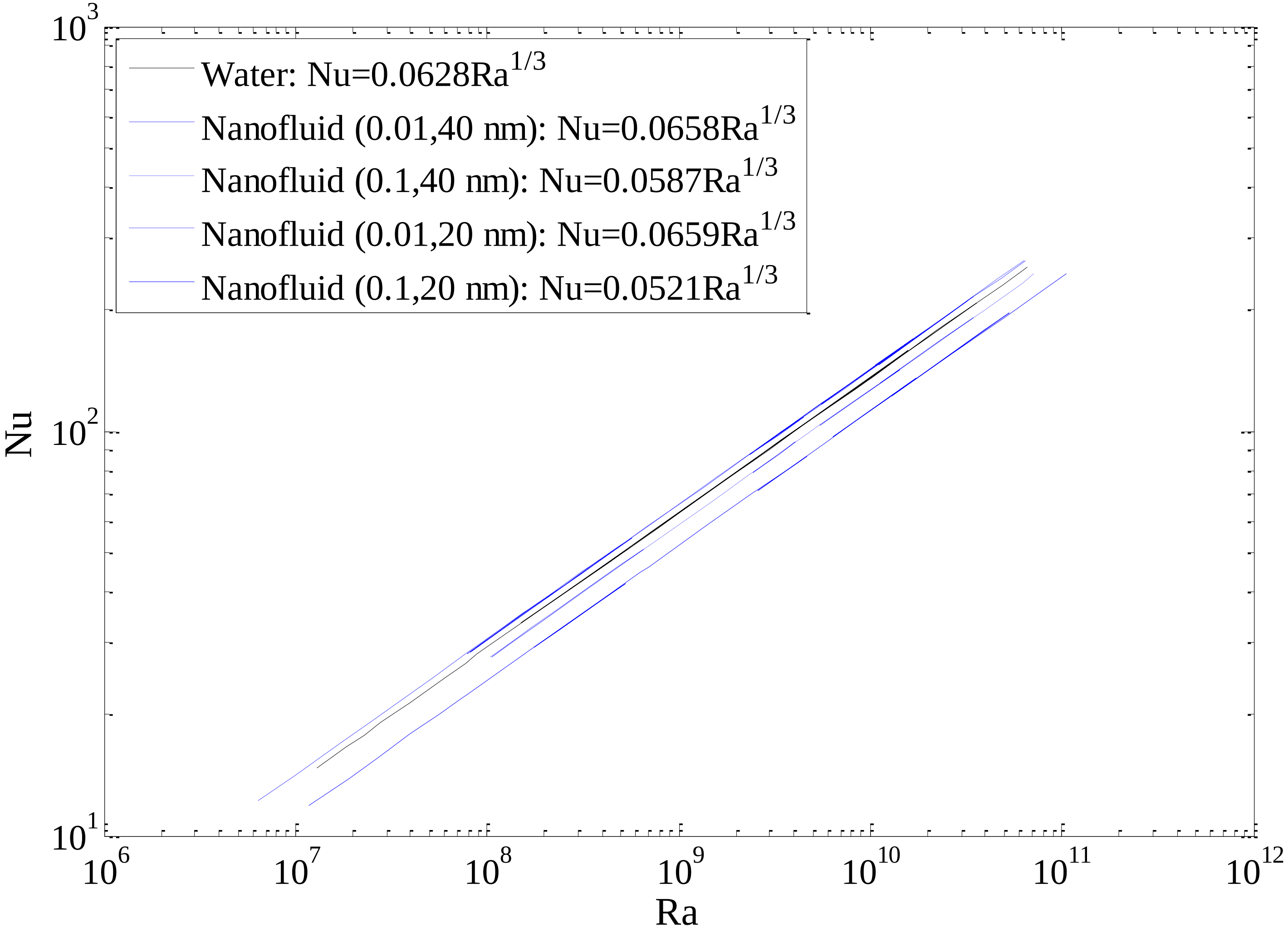
Nu-Ra plot for Nanofluids (ϕ=0.01% vol., d=40 mm)



Nu-Ra plot for Nanofluids (ϕ=0.1% vol., d=40 mm)



Nu-Ra plot for Nanofluids (ϕ=0.01,0.1% vol., d=40, 20 mm)



Conclusions

- Nanofluids of low concentrations have more Zeta Potential, hence more stable.
- TiO_2/water is more stable compared to Al_2O_3/water.
- Addition of surfactant increases the stability of nanofluids.
- R-B convection in both water and nanofluids satisfies Oberbeck-Boussinesq approximations in the temperature range covered in our experiments.
- Nu of R-B convection for the low concentration nanofluids(0.01% vol.) has higher than that of water, whereas it is lower for the case of high concentration nanofluids(0.1% vol.) .
- Nu for nanofluids having 20 nm nanoparticles is lower than that of nanofluids having 40 nm diameter nanoparticles.