Nanolubricants for Improving Chiller Performance

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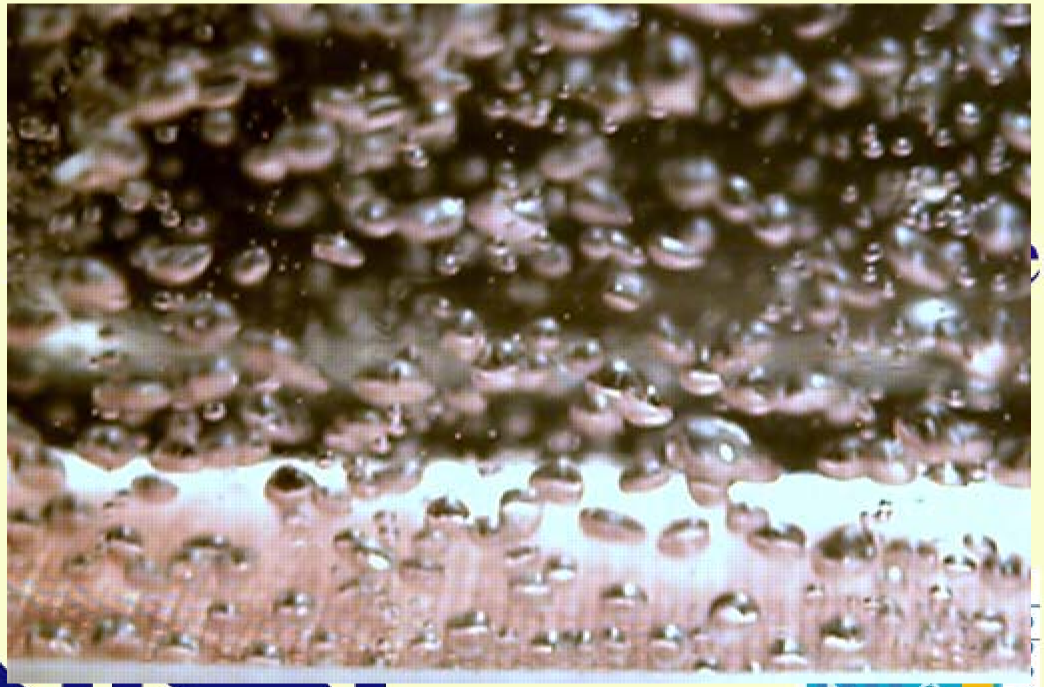


National ... echnology

Presentation Outline

Nanoparticle Basics

Review Boiling Measurement Results

....with Mechanistic Speculation

Boiling Model

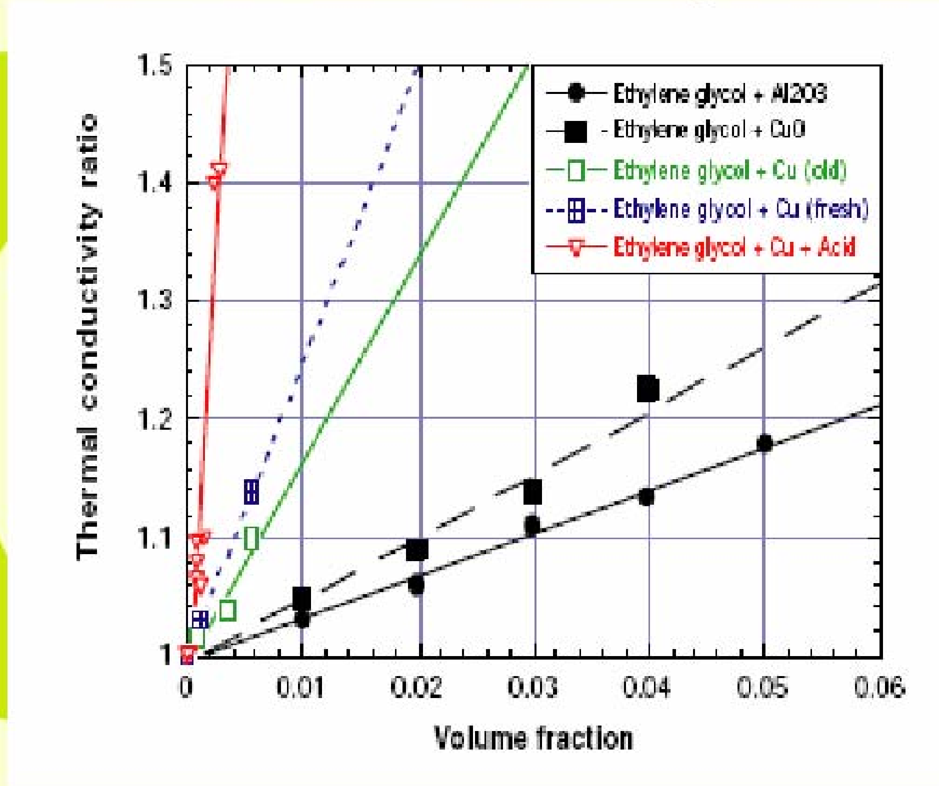
Viscosity Measurements and Model

Conclusions

Can Nanofluids Improve Refrigerant Boiling?

metal & metal-oxide dispersions

40 % improvement in thermal conductivity for a 0.4 % volume fraction



Appl. Phys. Lett. 78, 718-720, Eastman et al. (2001)

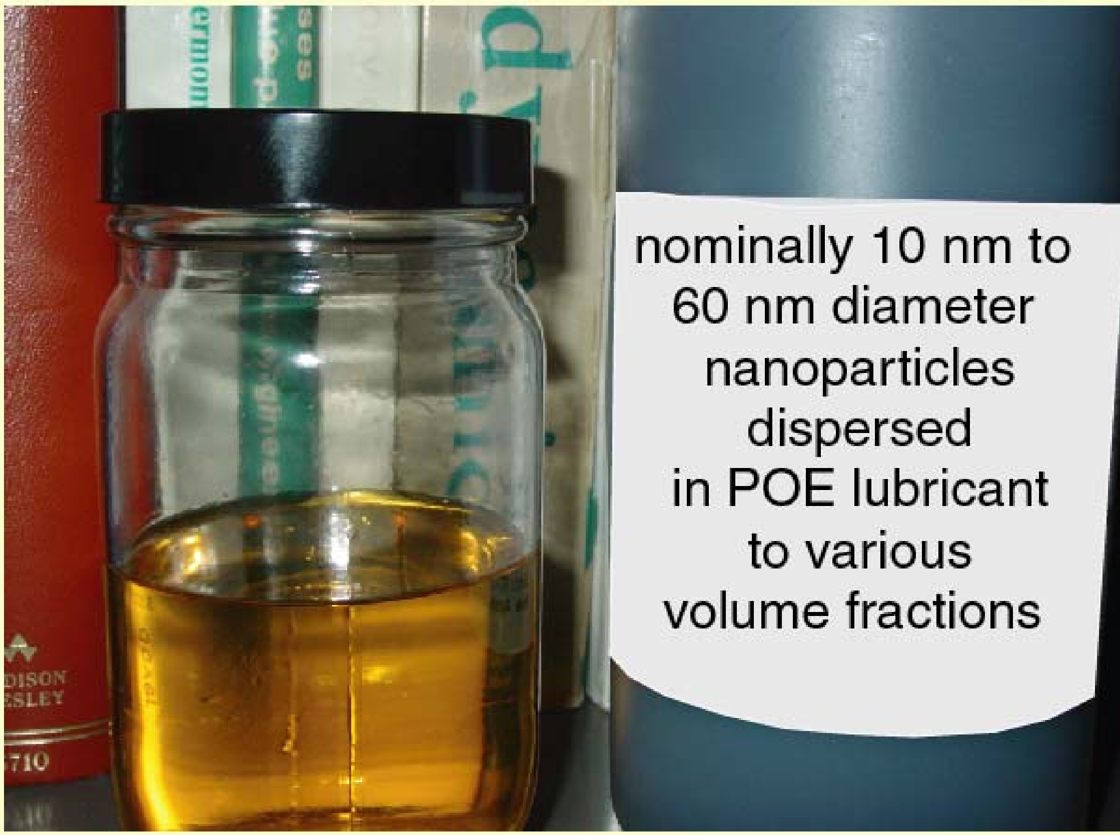
gives opportunity for improving air-conditioning chiller performance

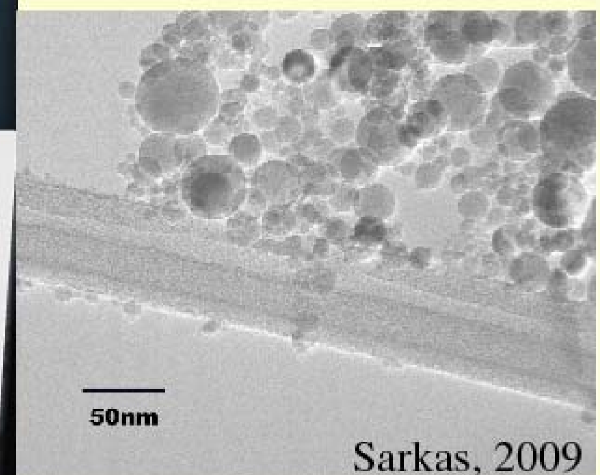
Potential Impact of Nanofluids for Chillers

If nanofluids improve chiller efficiency by 1 %, a savings of 320 billion kWh of electricity or an equivalent 5.5 million barrels of oil per year would be realized in the US alone

Lubricant Based, CuO, Al2O3, and Diamond Nanofluids

Base lubricant was a POE with a nominal kinematic viscosity of 72.3 $\mu m^2/s$ at 313.15 K



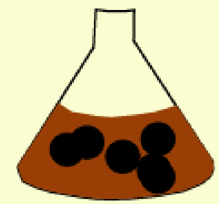


Nanoparticles Can Improve Refrigerant/Lubricant Boiling

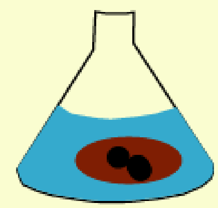
But this depends on the:

Properties of the nanoparticles:

Concentration of nanoparticles in nanolubricant:

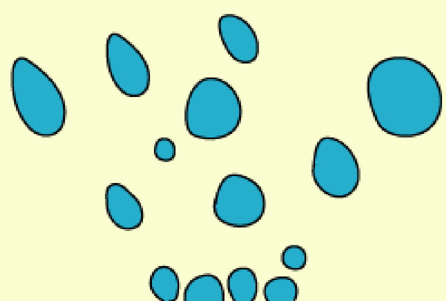


Concentration of nanolubricant in refrigerant:



Boiling heat flux:

other factors
(surface geometry, etc.)



gives opportunity for improving air-conditioning chiller performance

Semi-Empirical Model for Refrigerant/Nanolubricant Boiling Fitted to Single Constant

pure refrigerant properties

nanoparticle volume fraction

nanolubricant mass fraction

nanoparticle properties

$$\frac{q''_{\mathrm{np}}}{q''_{\mathrm{PL}}} = 1 + \frac{3.45\times 10^{-9}[\mathrm{s}]\,\phi\,\sigma\,\nu_{\mathrm{L}}\,\rho_{\mathrm{v}}\,x_{\mathrm{b}}^{2}}{\mathrm{D}_{\mathrm{np}}^{4}\left(q''_{\mathrm{n}}\right)^{3/2}\rho_{\mathrm{L}}\left(\rho_{\mathrm{np}}-\rho_{\mathrm{L}}\right)g(1-x_{\mathrm{b}})^{2}}$$

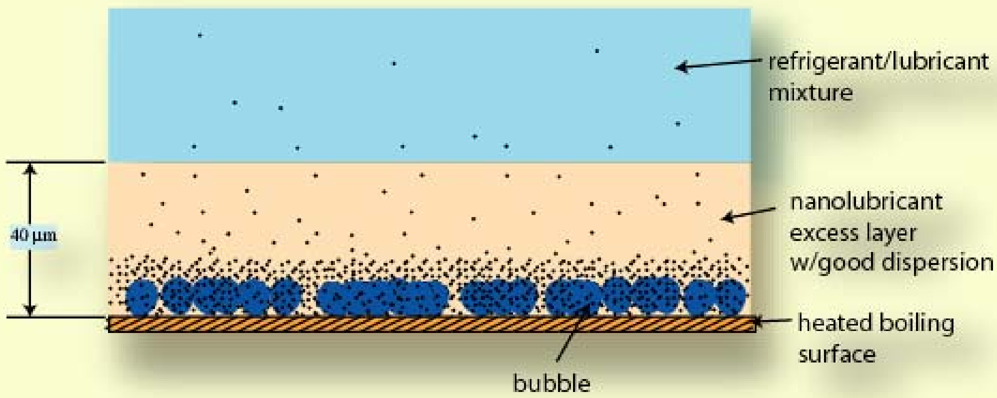
pure lubricant properties

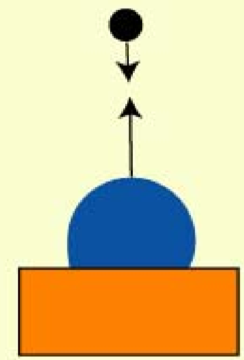
refrigerant/nanolubricant heat flux

refrigerant/pure lubricant heat flux

does not include the boiling enhancement due to the enhancement of the lubricant properties as contributed by the properties of the nanoparticles, but this could be easily included

Semi-Empirical Model for Refrigerant/Nanolubricant Boiling





M = mass

u = velocity

r = radius

D = diameter

N = number

Conservation of momentum for nanoparticles impacting a single bubble

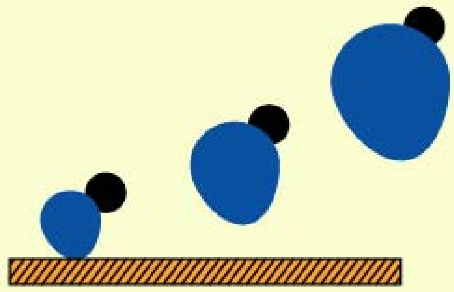
$$\frac{N_{np}}{N_b} M_{np} u_{np_i} + M_{b_i} u_{b_i} = \frac{N_{np}}{N_b} M_{np} u_{np_f} + M_{b_f} u_{b_f}$$

Change in kinetic energy of the nanoparticle is equal bubble surface work

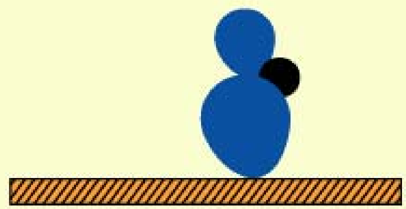
$$\frac{1}{2} M_{np} u_{np_f}^2 - \frac{1}{2} M_{np} u_{np_i}^2 = 4\pi\sigma(r_{b_f'}^2 - r_{b_i'}^2)$$

Proposed Enhancement Mechanism

enhanced bubble growth caused by bubble/ "hot" particle interation

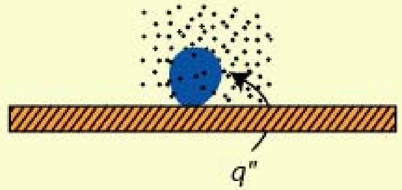


secondary nucleation on "hot" partical in fluid

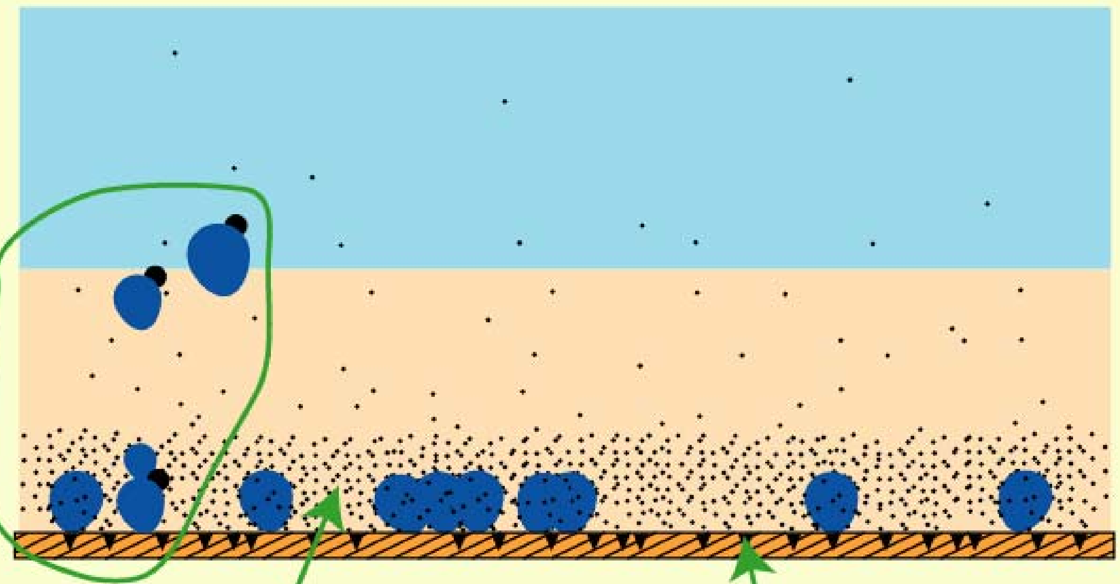


particle momentum transfer to bubbles

Bubbles grow through nanoparticles that are suspended in the lubricant excess layer, thus, performing surface work on the bubbles

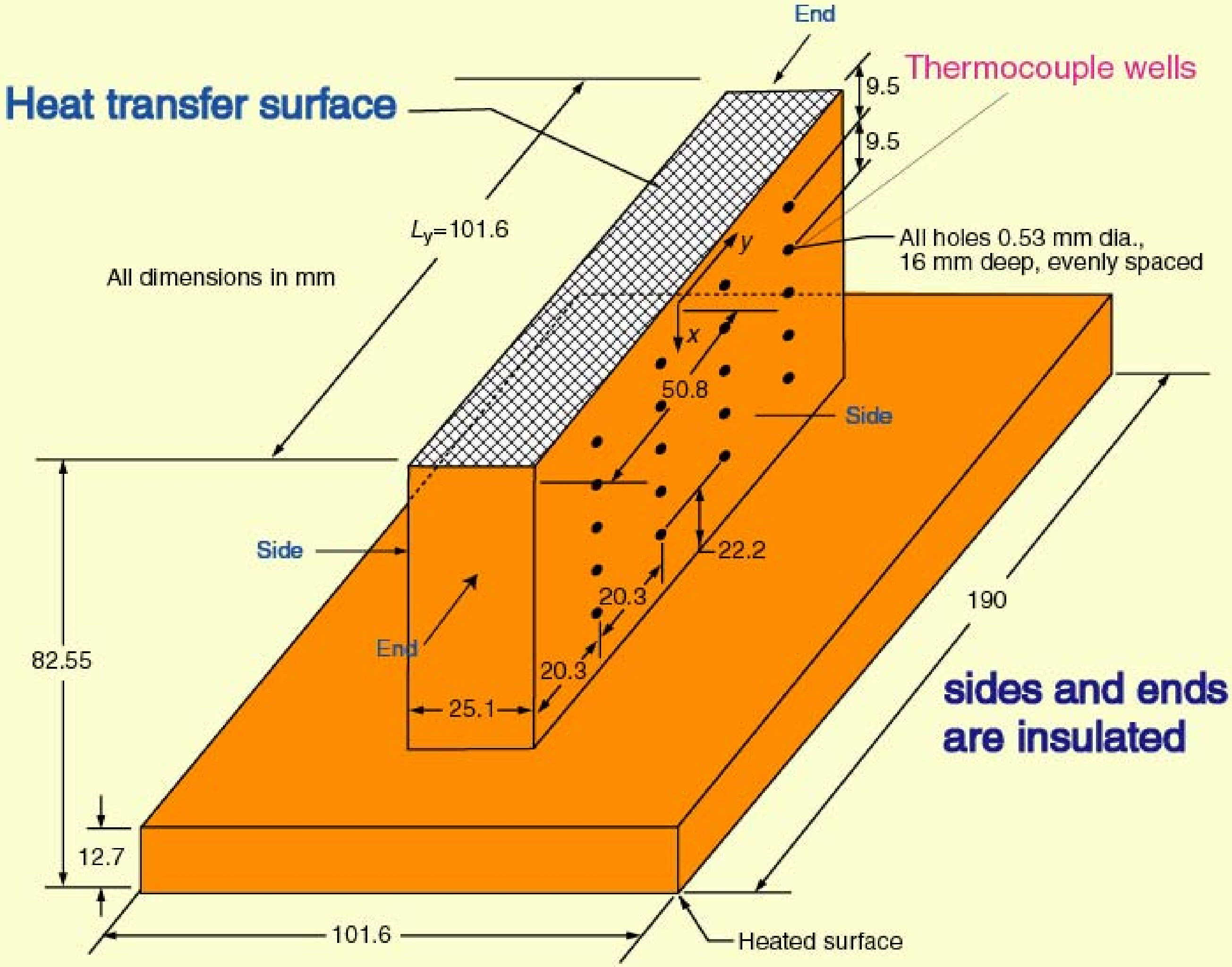


Enhancement or Degradation Realized Based on the Coupling of three heat transfer mechanisms:

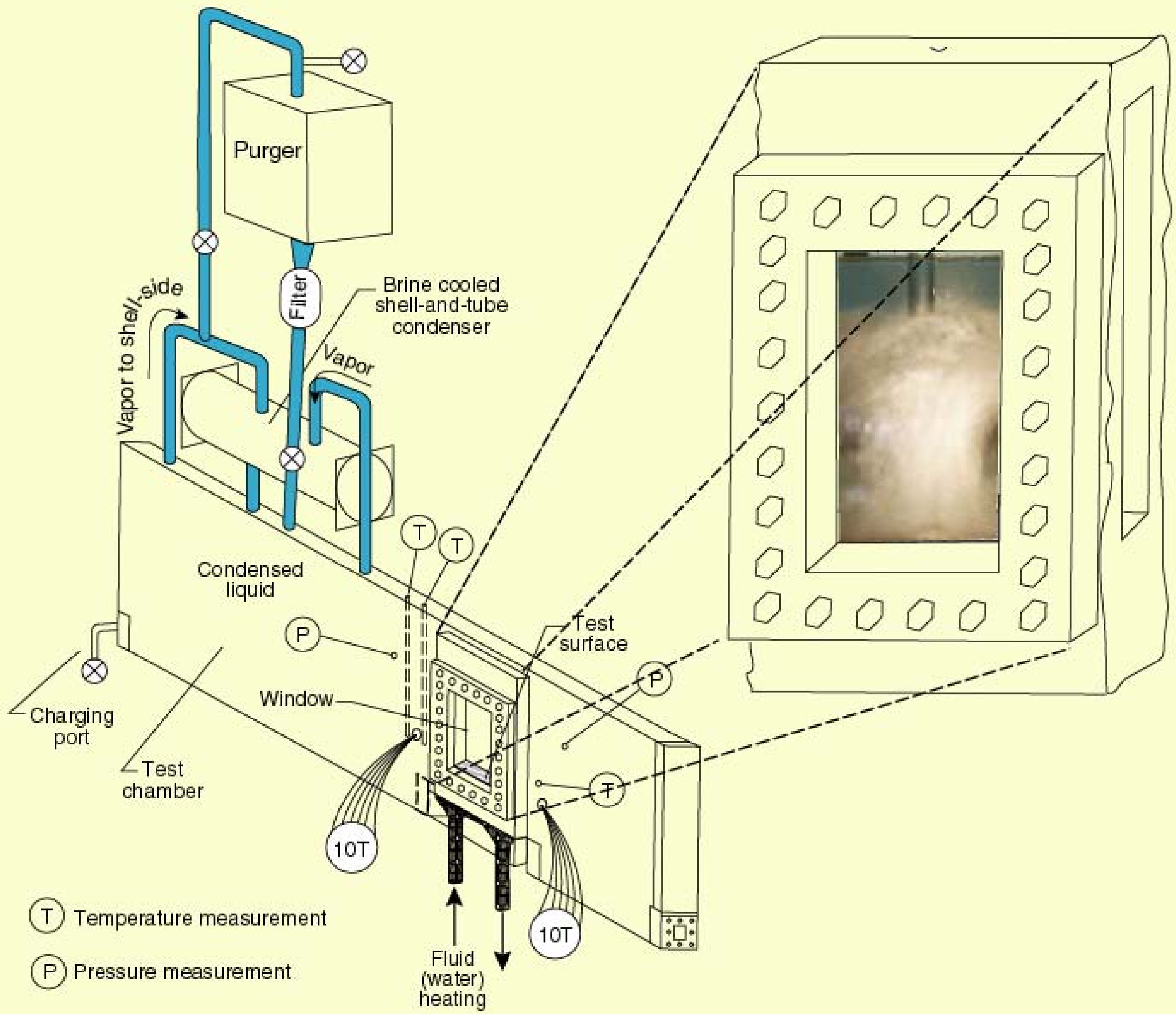


Volume fraction determines if enough particles remain from mechanism (3) to be used in mechanisms (1) and (2)

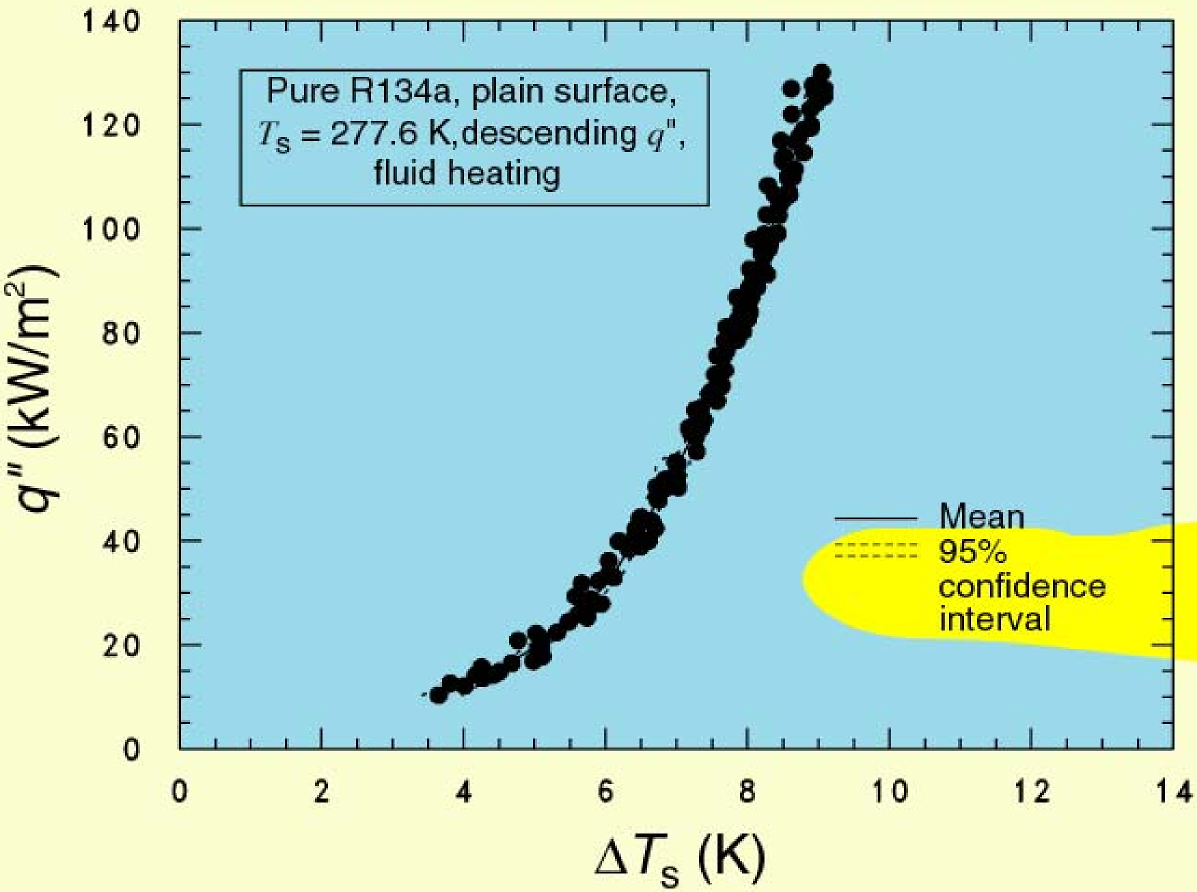
OFHC Test Surface



Schematic of Test Apparatus



Pure R134a Pool Boiling

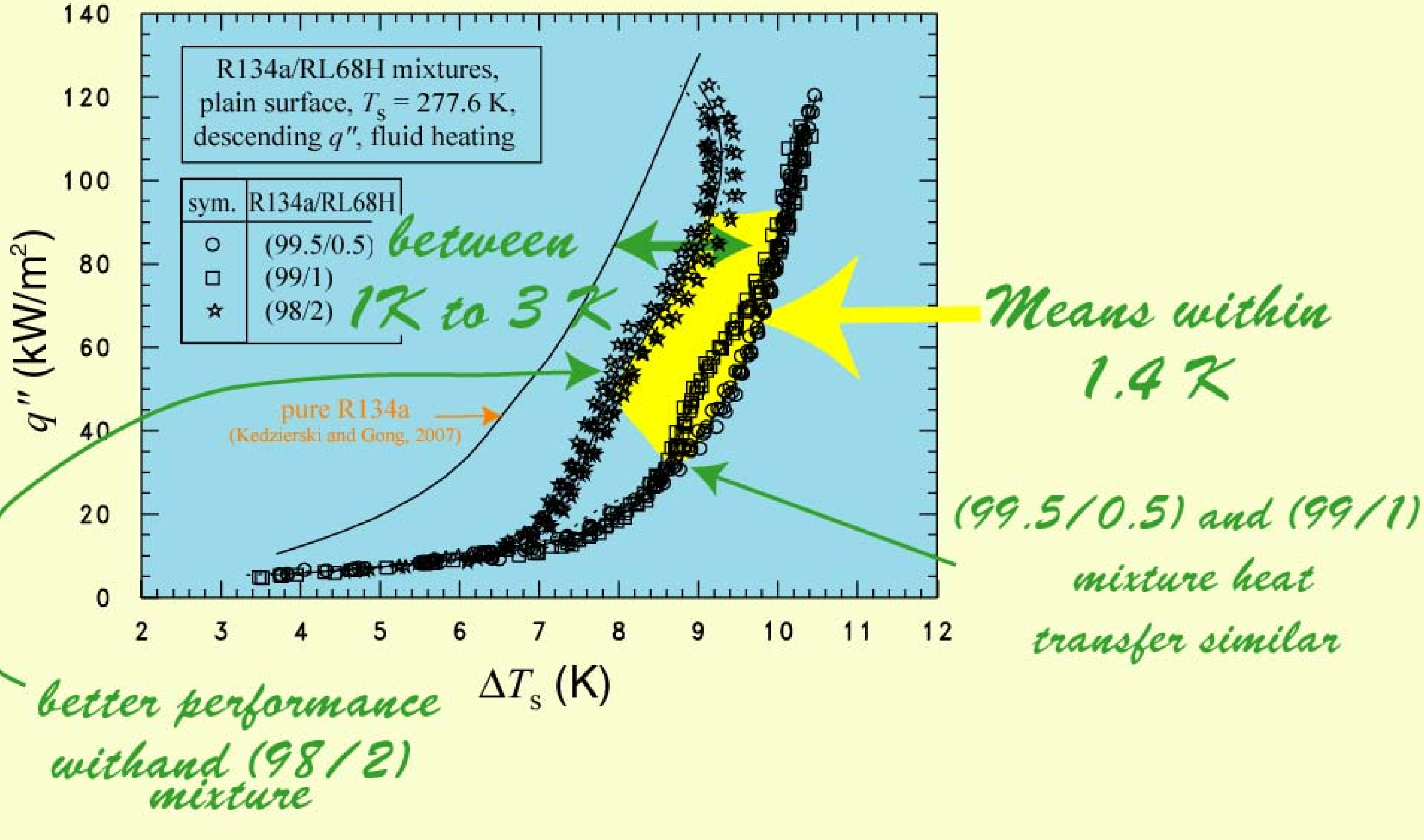


145 pts. taken
over 13 days

apprx.
± 0.1 K

Effect of Pure Lubricant on Boiling

(Three Mixtures Tested)



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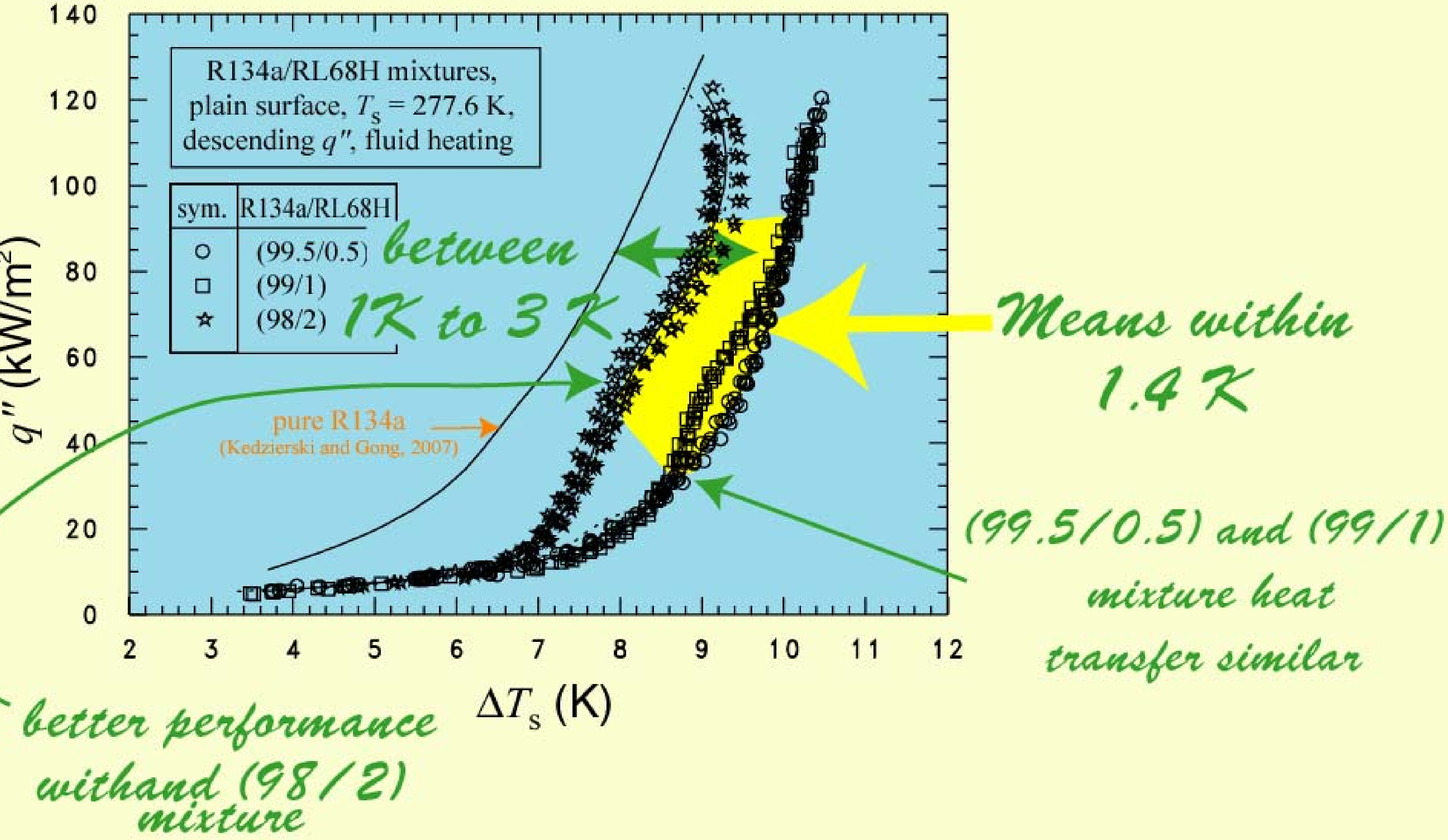
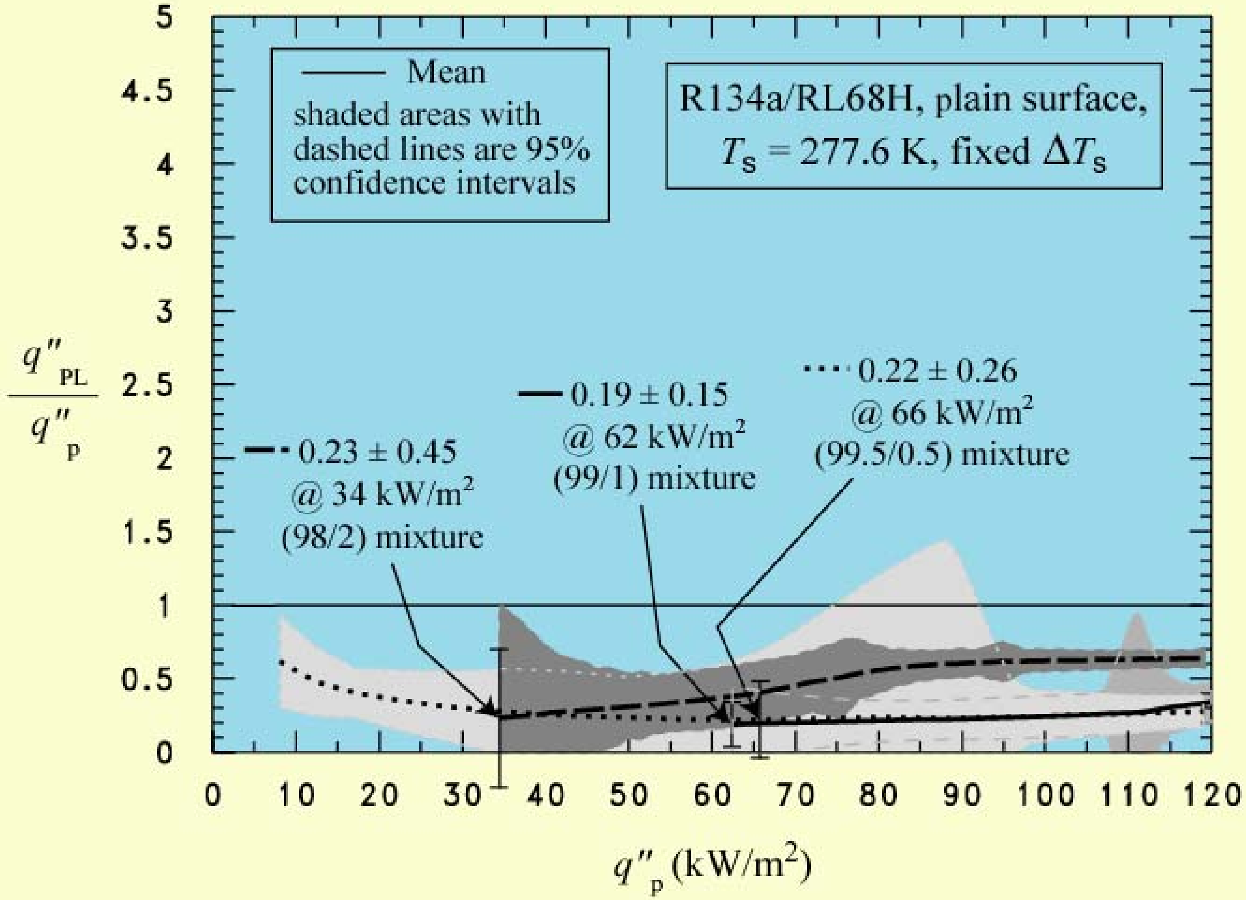
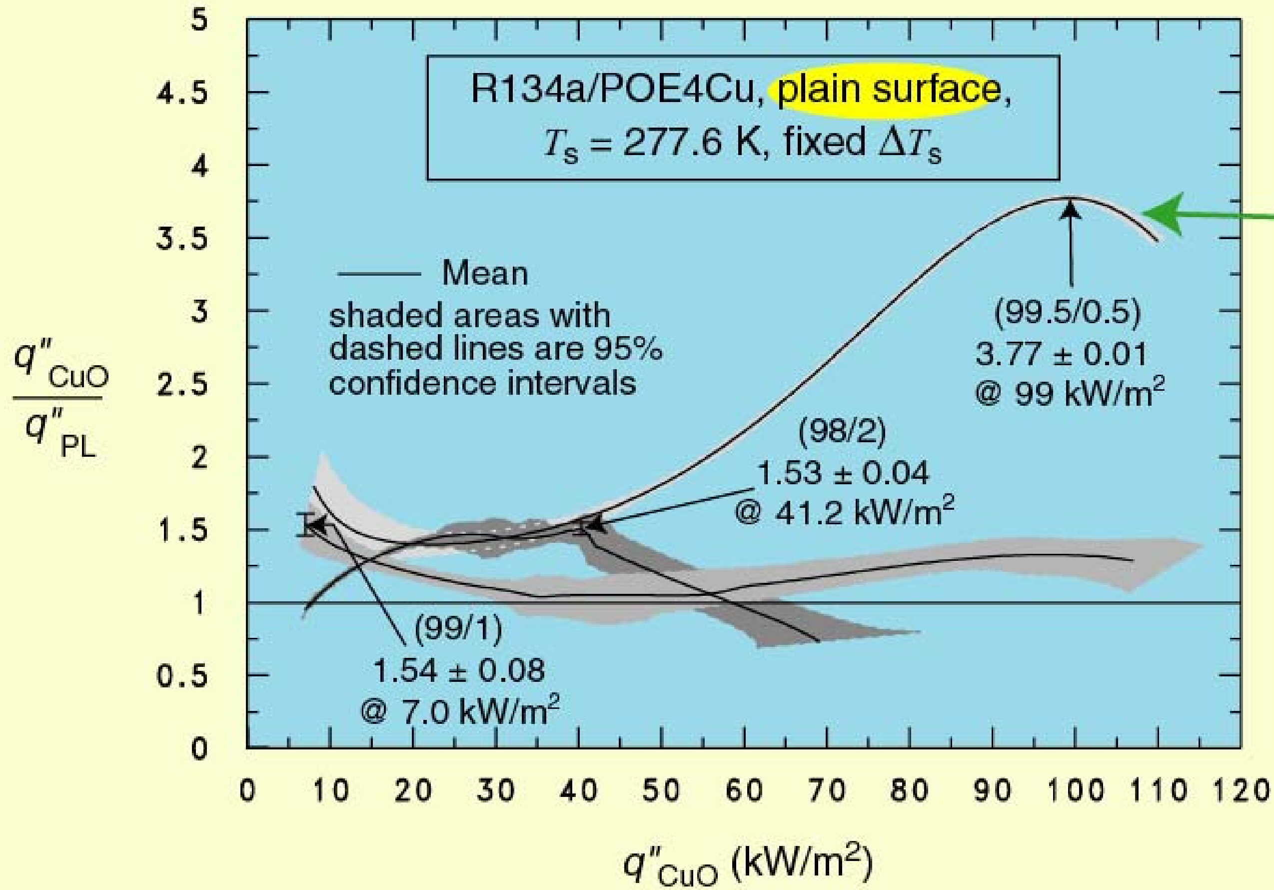


Effect of Pure Lubricant on R134a Boiling



Degradation similar for each lubricant mass fraction

Effect of 4% Vol. Fraction CuO Nanoparticles on Boiling



0.5% mixture is roughly between 1.5 and 3.75

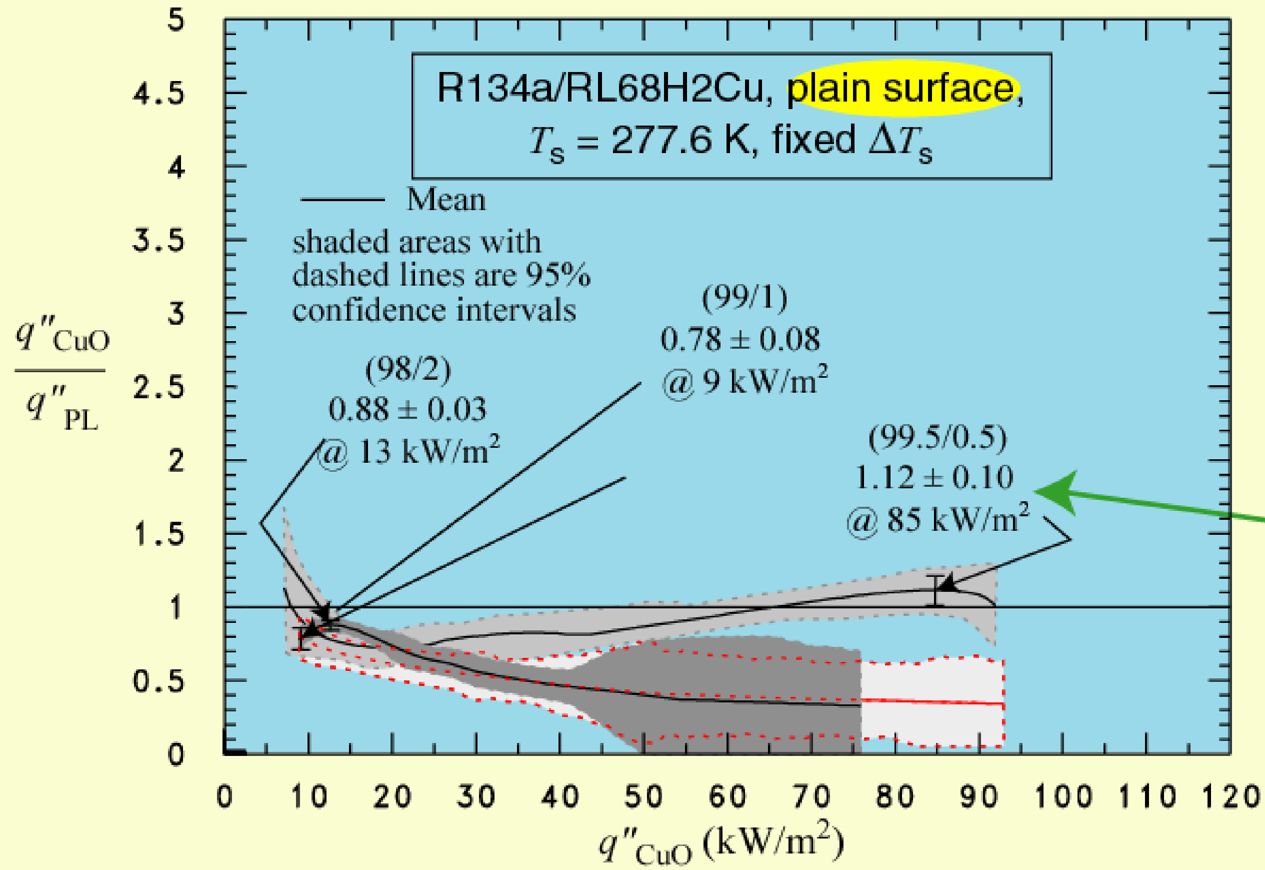
Average ratio:

0.5% → 2.4

1% → 1.19

2% → 1.12

Effect of 2% Vol. Fraction CuO Nanoparticles on Boiling

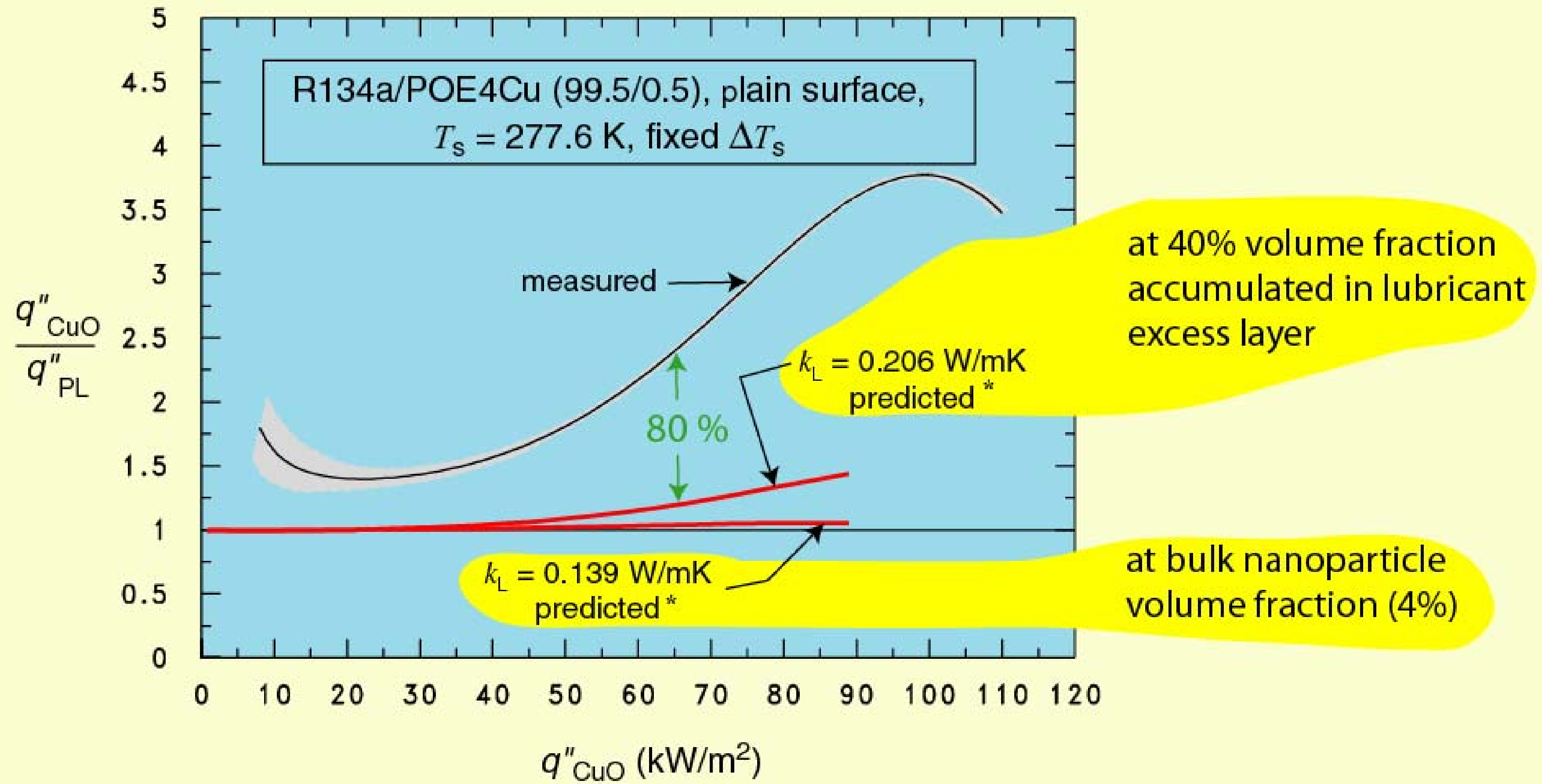


Average ratio:
0.5% → 0.9
1% → 0.4
2% → 0.5

0.5% mixture is roughly between 0.73 and 1.12

Degradation may be due to fill of nano-size cavities causing a loss in active sites

Effect of Increased k_L on Boiling

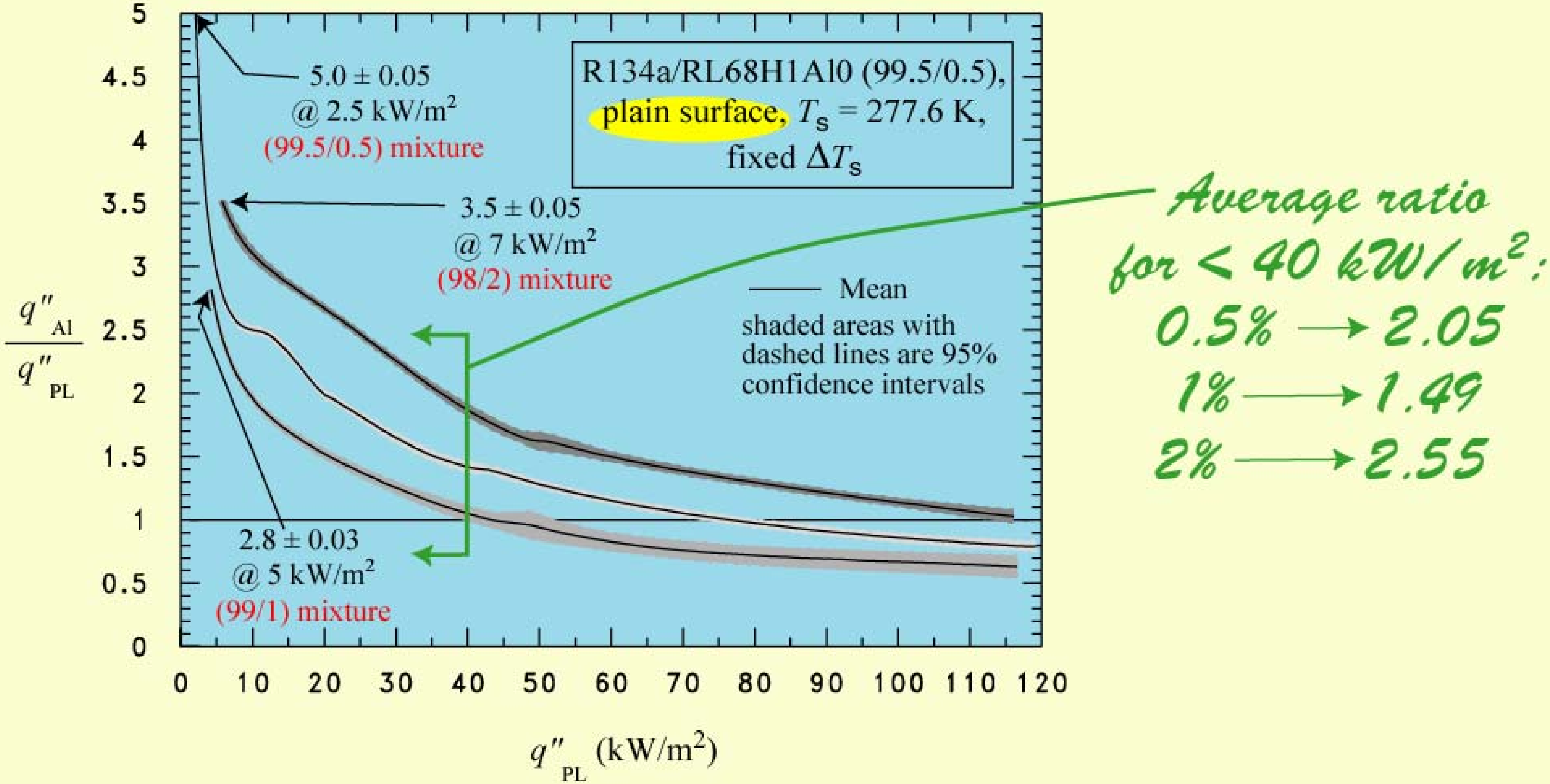


Approx 20 % of the enhancement may be due to increased thermal conductivity

*Refrigerant/lubricant pool boiling model Kedzierski 2003 ICR

Effect of Al_2O_3 Nanolubricant on R134a Boiling

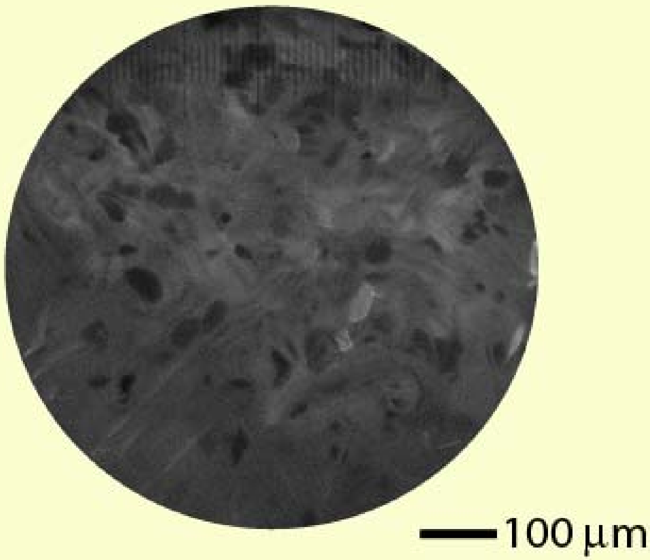
Aluminum oxide nanoparticles provided the most favorable benefit to the 2 % mass fraction mixture



Enhancement occurred for the lowest heat fluxes giving the opportunity for chillers with lower approach temperatures

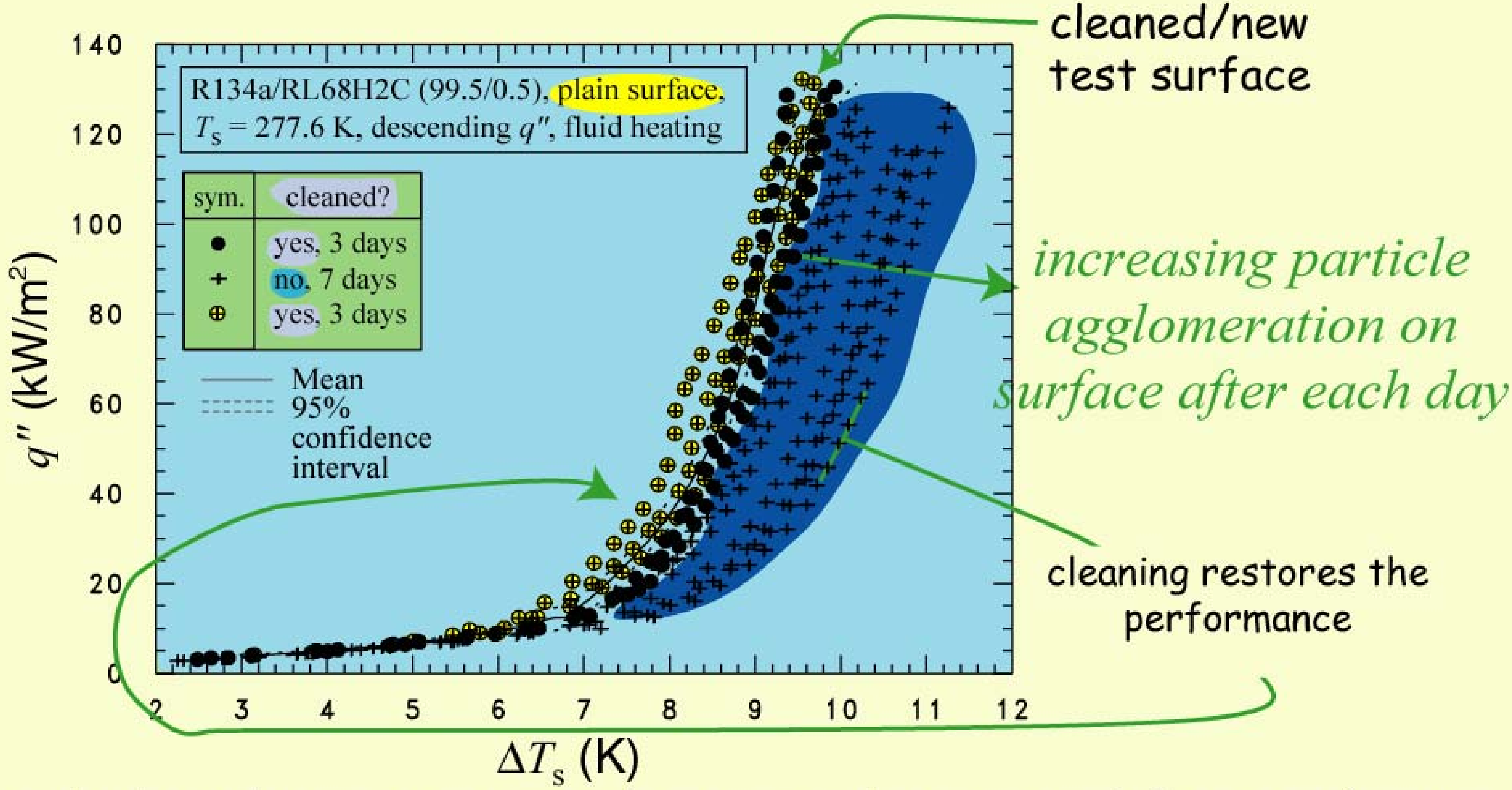
Very Polydispersed Diamond Nanolubricant

Dynamic Light Scattering (DLS) and sieving technique using a syringe filter and an optical microscope



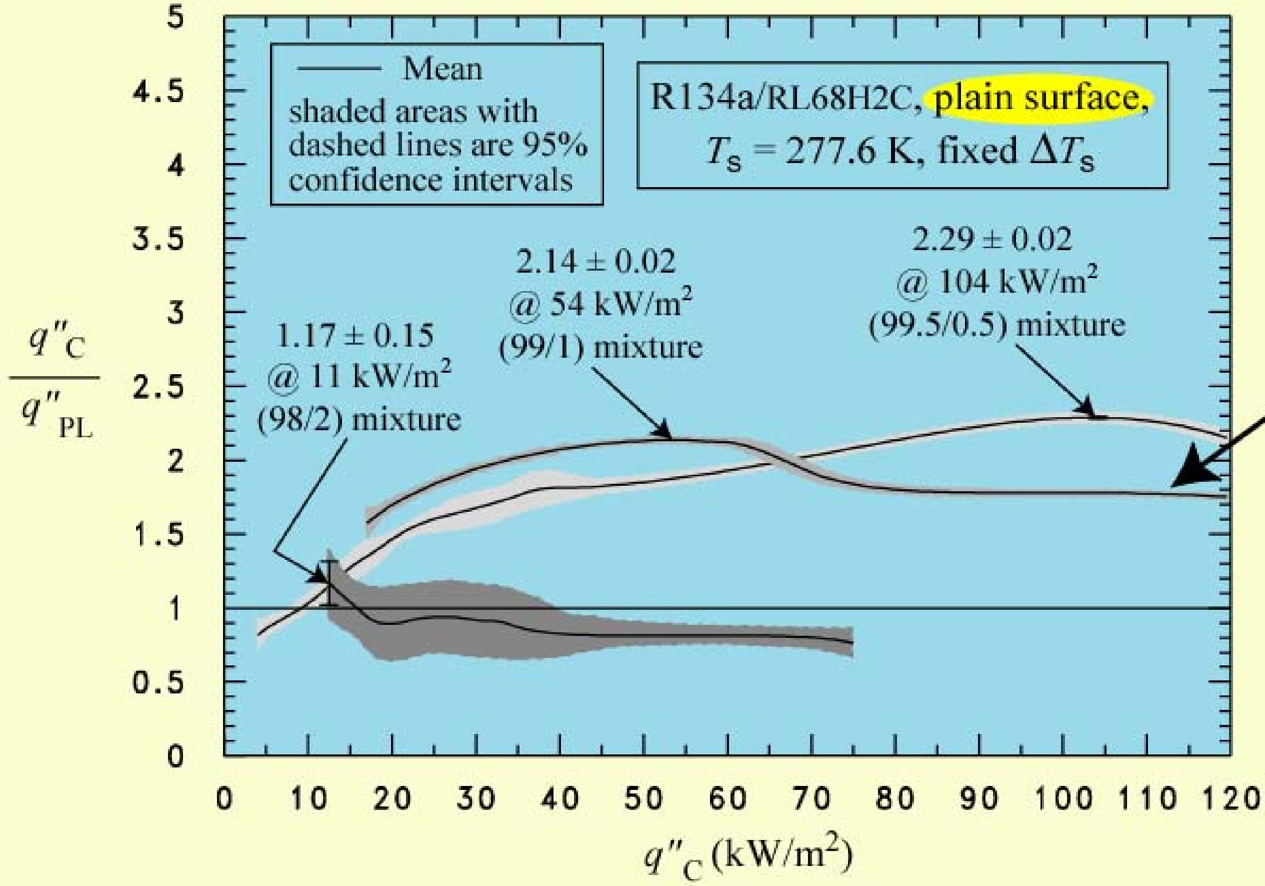
The particles are dispersed from single 10 nm diameter particles to agglomerations of particles as large as 50 mm.

Effect of Particle Agglomeration on R134a/Diamond Nanolubricant boiling



degradations increase as agglomerated nanoparticles settle out of the excess layer and into the cavities of the boiling surface

Effect of Diamond Nanolubricant on Boiling (best performance)



0.5% mixture is roughly between 0.8 and 2.29

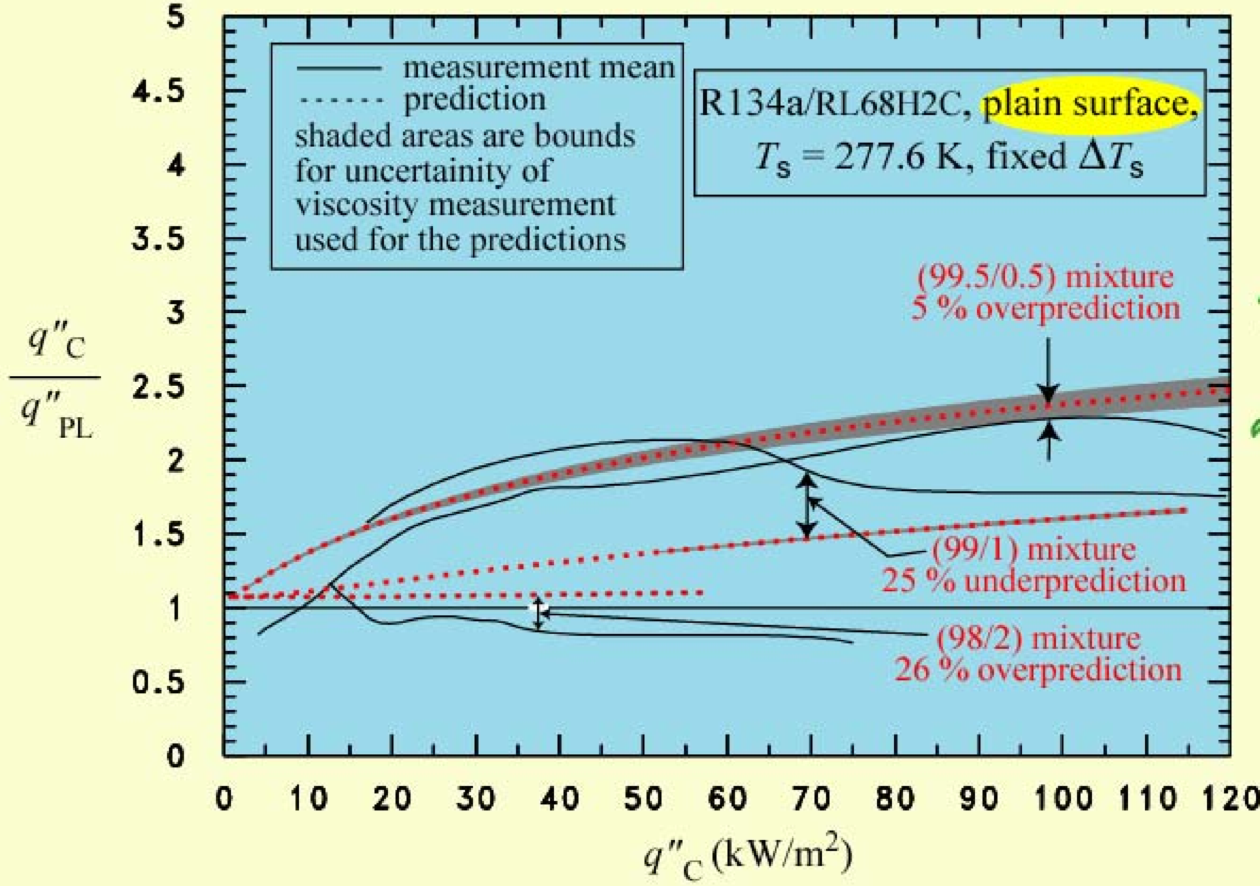
1% mixture is never less than 1.5

Average ratio:
0.5% → 1.98
1% → 1.91
2% → 0.81

Sustainable improvement for wide heat flux range

Increased Viscosity Caused Enhancement (not particle interaction)

kinematic viscosity increased by 550%

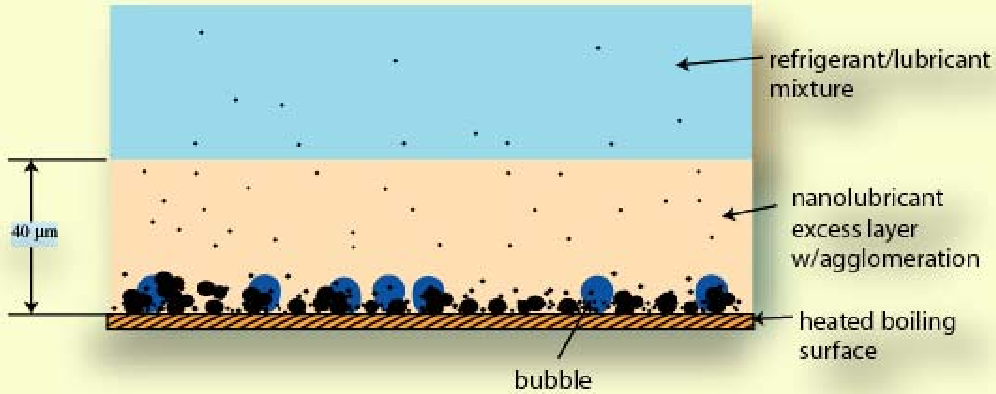


Model can predict only property effects, not nanoparticle interaction with bubbles

Refrigerant/lubricant boiling model predicts enhancement based on viscosity increase

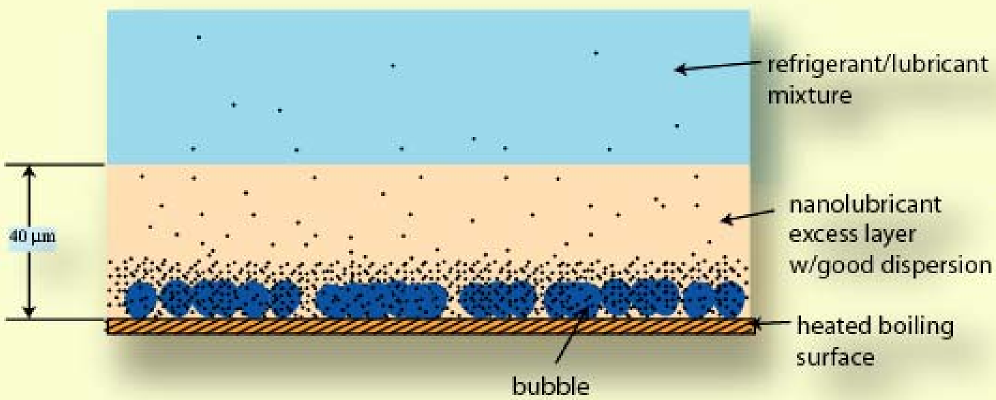
*Refrigerant/lubricant pool boiling model Kedzierski IJR 2003

Particle Interaction with Bubbles Depends on the Quality of the Dispersion



Bad Dispersion

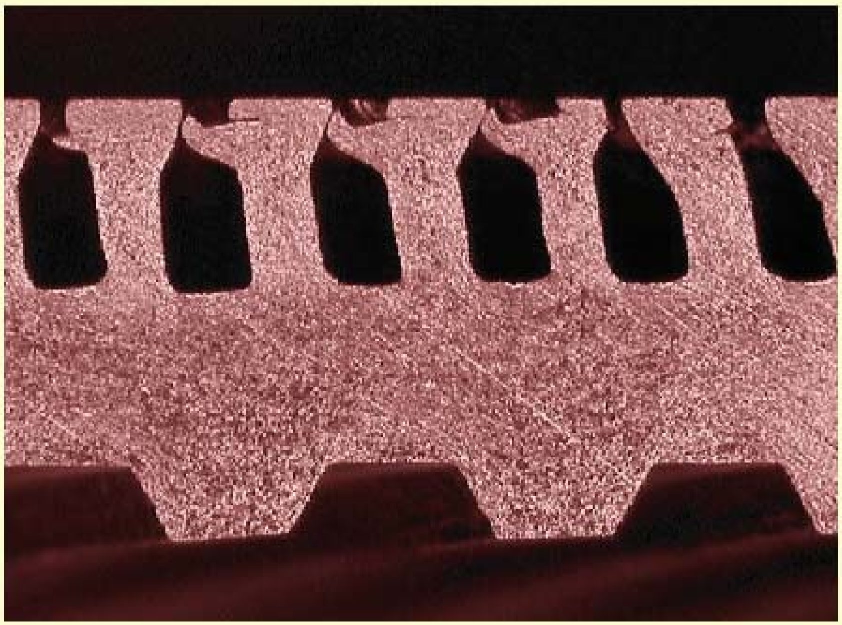
Particles don't remain suspended in excess layer



Good Dispersion

Particles remain suspended to interact with bubbles

Photograph of Reentrant Cavity Boiling Surface



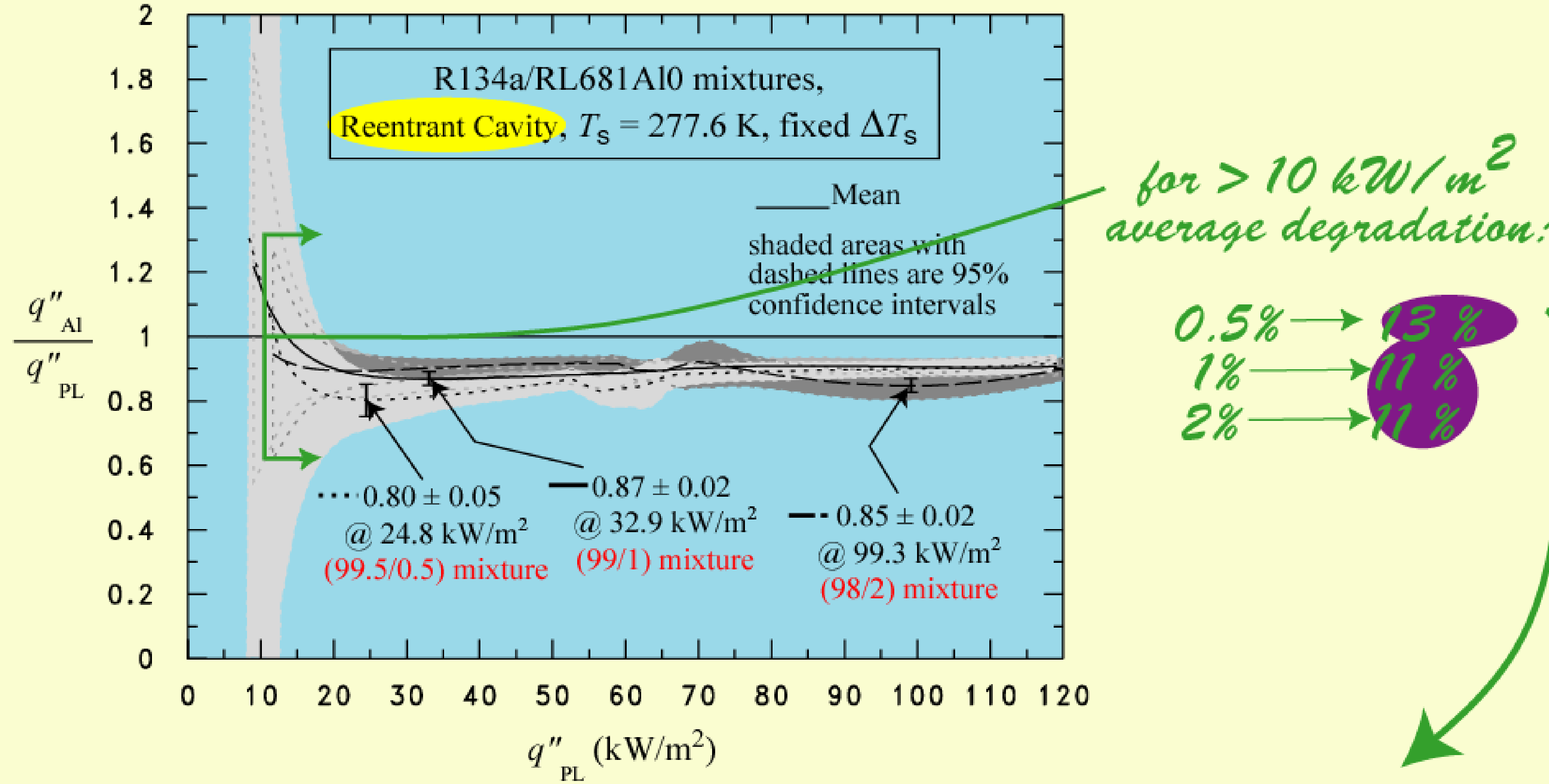
– 0.1 mm

SIDE VIEW

– 0.1 mm

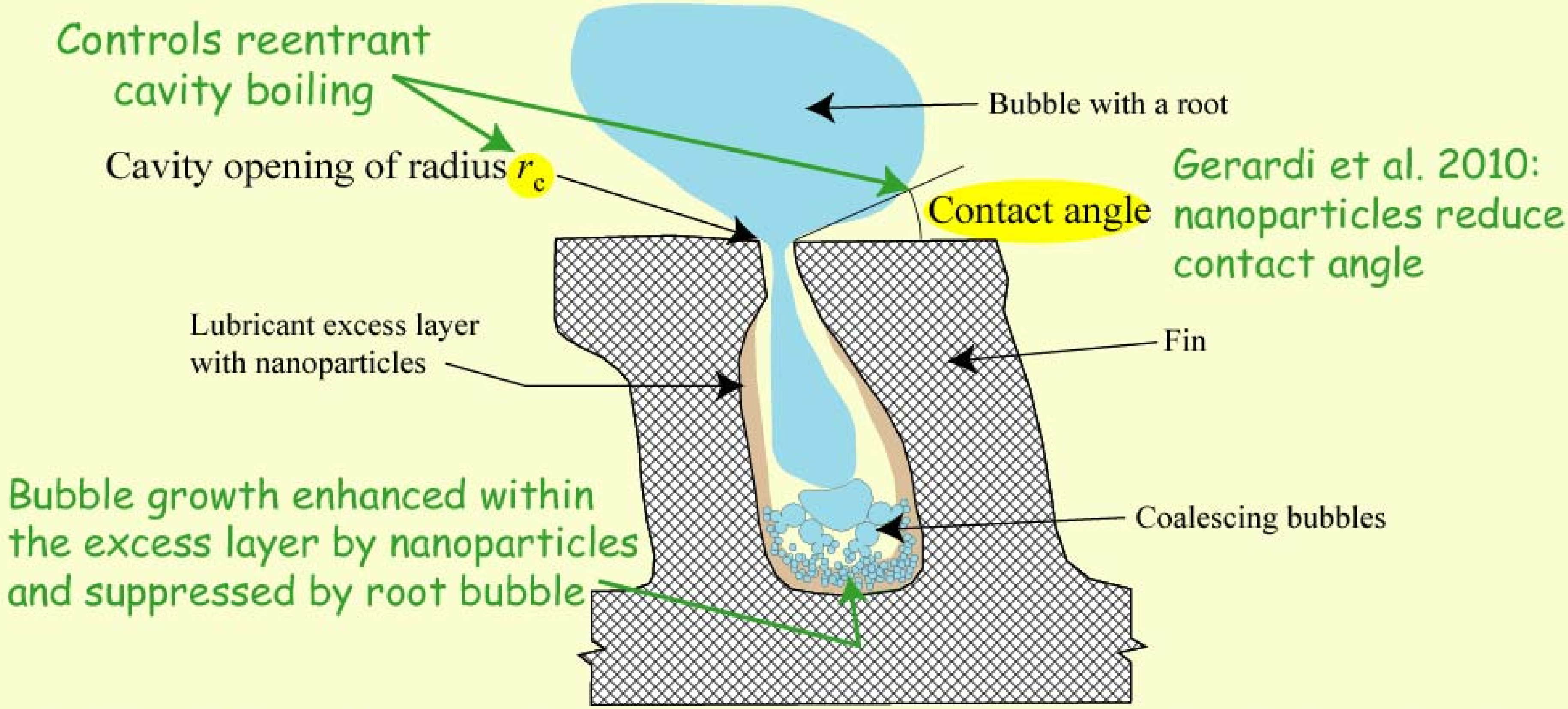
TOP VIEW

Effect of Al_2O_3 Nanolubricant on Reentrant Cavity Boiling



Enhancement mechanism of the nanoparticles made redundant by the reentrant cavities of the boiling surface

R134a/Nanolubricant Boiling Mechanism in Reentrant Cavity

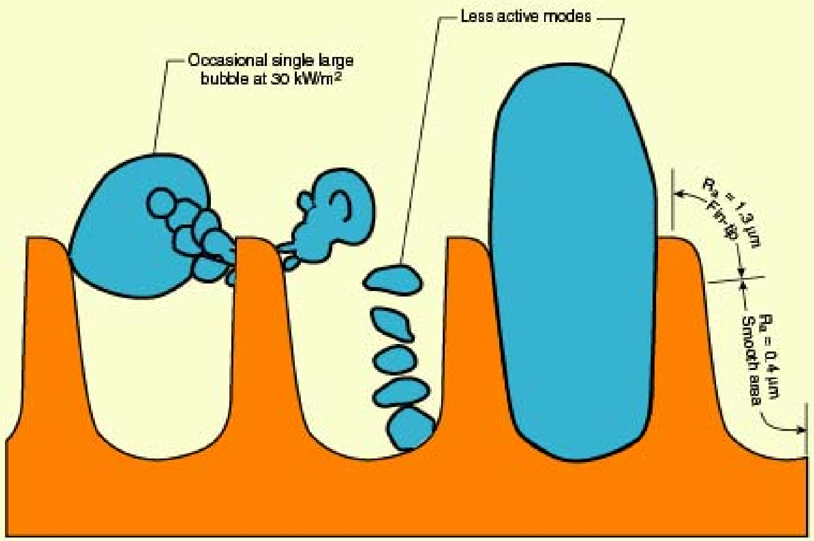


Positive effect of nanoparticles reduced because bubble nucleation in cavity less important and suppressed

Negative effect of reduced contact angle likely cause of 12 % degradation

Current Work: Open Fin

Trapezoidal finned tubes have water-side enhancements



Four different modes of bubble evolution

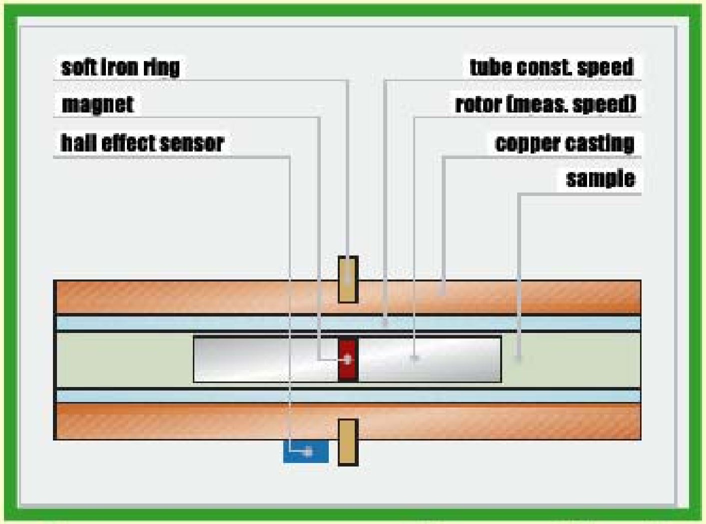
Performance governed more so by bubble nucleation

Improved potential for nanoparticles to enhance boiling performance

Switch Gears from Boiling Measurements to Measurement of the Viscosity and the Density of Nanolubricants for Several Al_2O_3 Mass Fractions and Several Surfactant Mass Fractions

Stabinger Viscometer

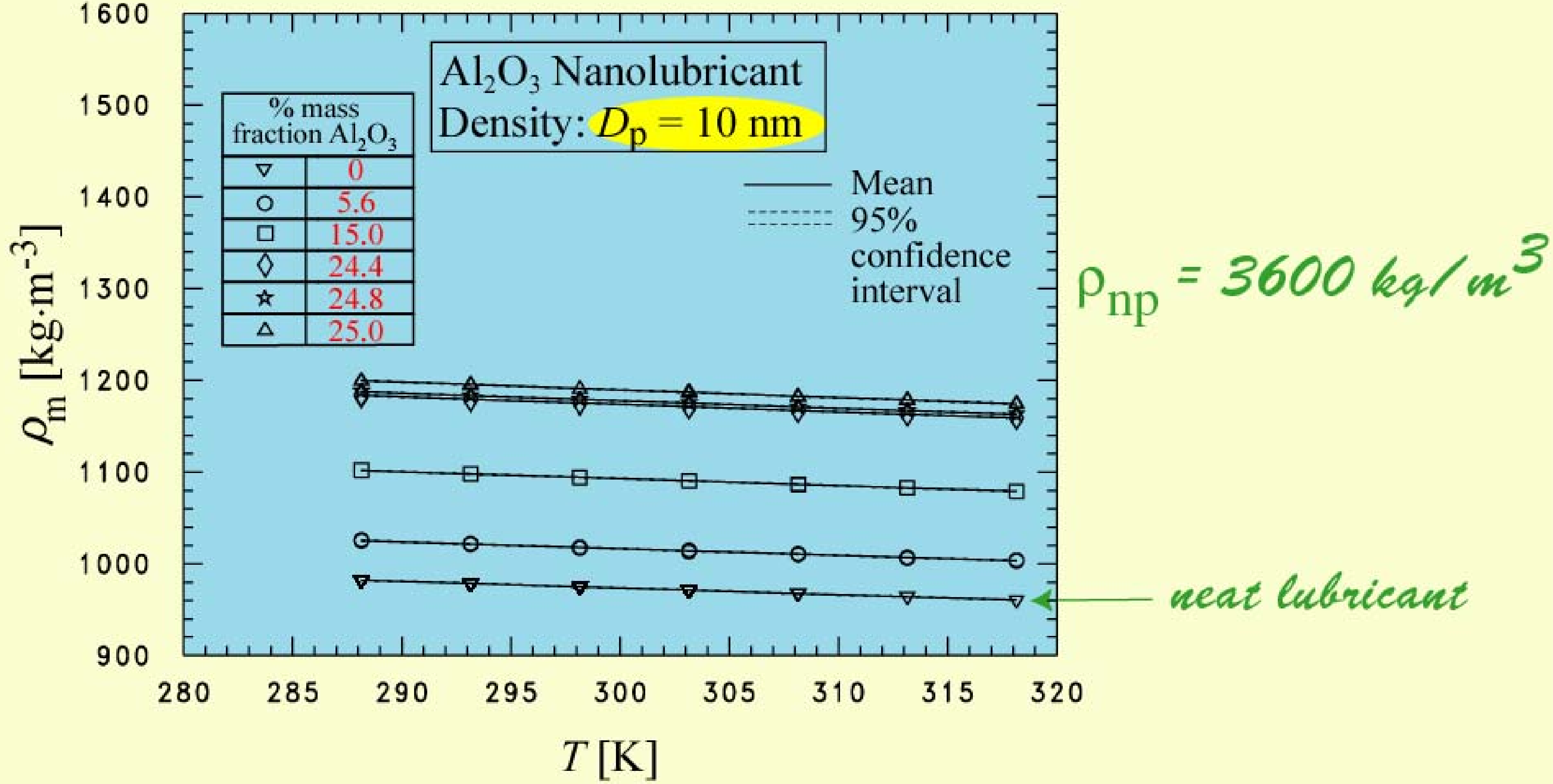
Difference in speed and torque between the outer and inner cylinder is used to determine the dynamic viscosity.



rotating concentric cylinders

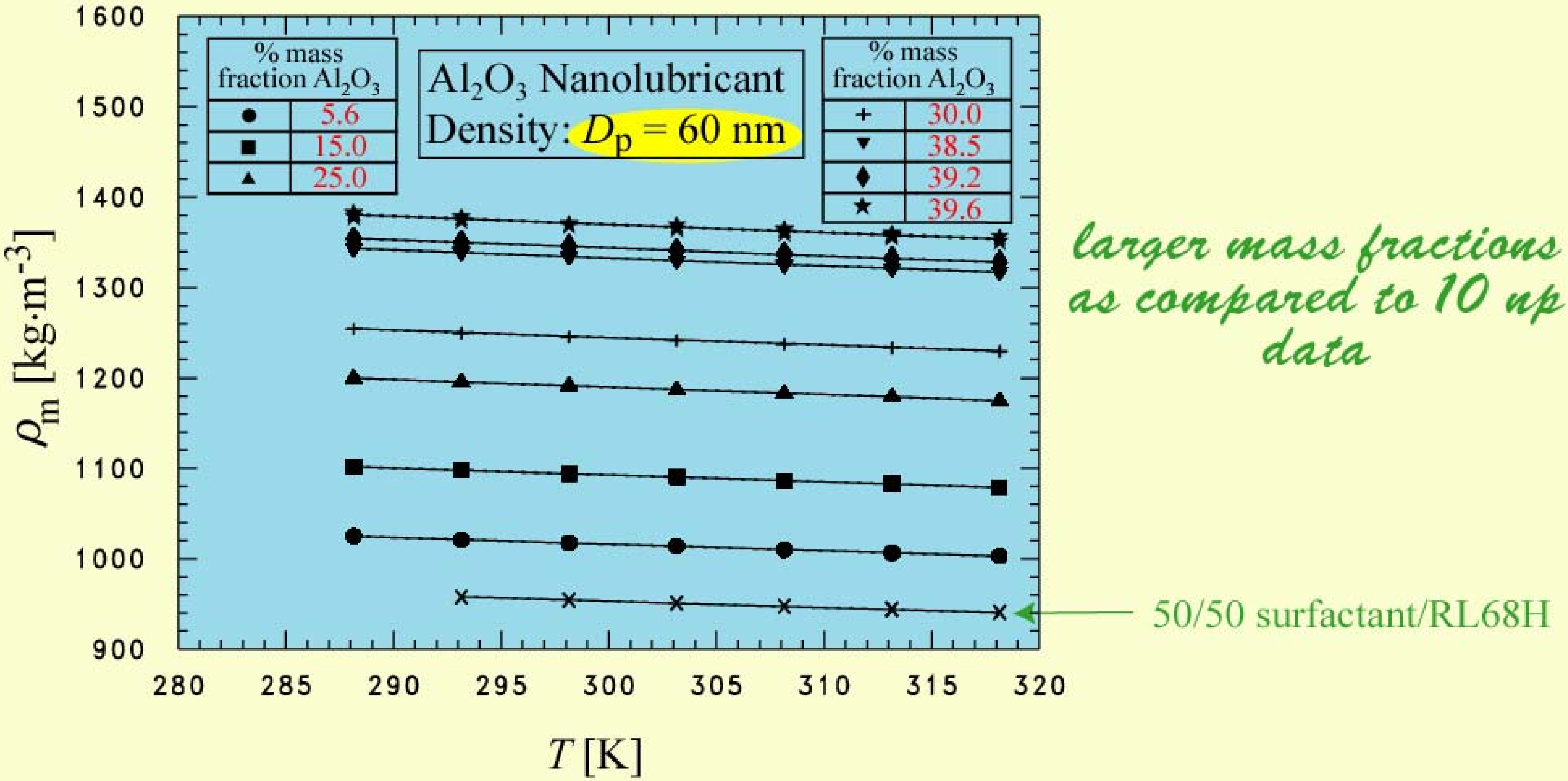
Manufacturer quoted uncertainty for the kinematic viscosity and the density was ± 0.35 % and ± 0.5 kg·m-3

Density of Nanolubricant for Several Al_2O_3 Mass Fractions



Density decreases with temperature and increases with mass fraction as expected

Density of Nanolubricant for Several Al_2O_3 Mass Fractions



Nanoparticle size does not appear to affect the density

Linear Fit of Specific Volume with Respect to Temperature

$$\rho_{m}^{-1}[m^{3} \bullet kg^{-1}] = B_{0} + B_{1}T[K]$$

Nanoparticle mass fraction

x_{np}	x_s	x_L	D_p (nm)	U_p (%)	Fitted Constant		Residual standard deviation of fit (%)
					B_0	B_1	
0	0	1.0	N/A	0.24	0.7979×10^{-3}	0.7647×10^{-6}	0.11
0.056	0.014	0.930	10	0.38	0.7689×10^{-3}	0.7164×10^{-6}	0.19
0.056	0.011	0.933	60	0.27	0.7702×10^{-3}	0.7132×10^{-6}	0.13
0.150	0.038	0.812	10	0.25	0.7232×10^{-3}	0.6399×10^{-6}	0.12
0.150	0.030	0.820	60	0.25	0.7224×10^{-3}	0.6429×10^{-6}	0.12
0.250	0.062	0.688	10	0.30	0.6617×10^{-3}	0.5964×10^{-6}	0.15
0.250	0.050	0.700	60	0.23	0.6638×10^{-3}	0.5887×10^{-6}	0.11
0.248	0.078	0.674	10	0.23	0.6707×10^{-3}	0.5945×10^{-6}	0.11
0.244	0.091	0.665	10	0.23	0.6728×10^{-3}	0.5975×10^{-6}	0.11
0.300	0.060	0.640	60	0.21	0.6434×10^{-3}	0.5334×10^{-6}	0.10
0.396	0.079	0.525	60	1.23	0.5870×10^{-3}	0.4767×10^{-6}	0.62
0.392	0.098	0.510	60	0.21	0.5981×10^{-3}	0.4869×10^{-6}	0.10
0.385	0.115	0.500	60	0.21	0.6015×10^{-3}	0.4964×10^{-6}	0.10
0	0.500	0.500	N/A	0.24	0.8211×10^{-3}	0.7607×10^{-6}	0.11
0	1.0	0	N/A	0.34	0.8443×10^{-3}	0.7567×10^{-6}	N/A

surfactant mass fraction

pure lubricant mass fraction

nanoparticle diameter

All Specific Volume Predicted Within 1 % With Wasp et al. (1977):

$$\frac{1}{\rho_{\mathrm{m}}} = \frac{x_{\mathrm{s}}}{\rho_{\mathrm{s}}} + \frac{x_{\mathrm{L}}}{\rho_{\mathrm{L}}} + \frac{x_{\mathrm{np}}}{\rho_{\mathrm{np}}}$$

MIXTURE

SURFACTANT

LUBRICANT

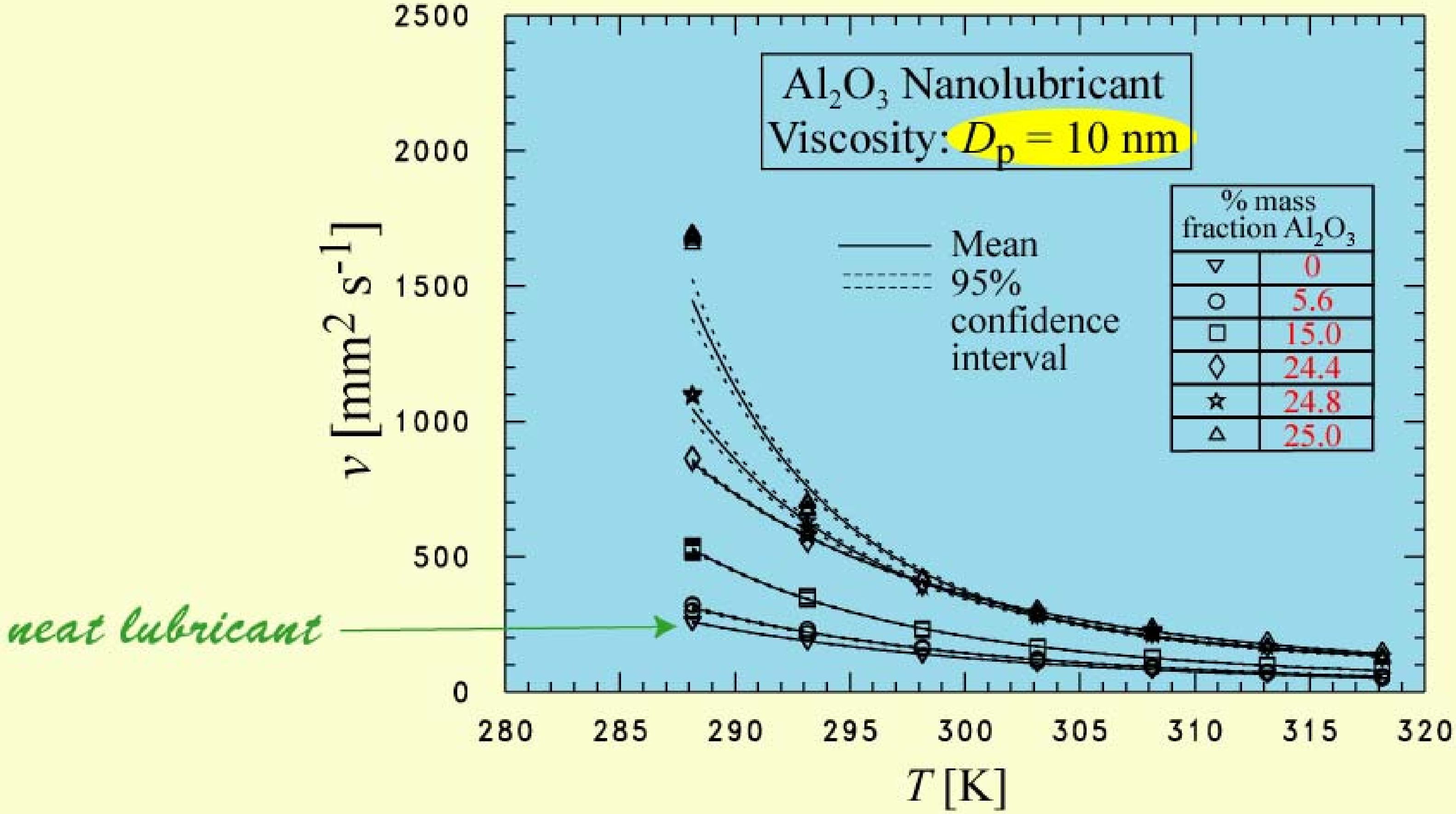
NANOPARTILCE

within 0.5 % for mass fractions less than or equal to 0.3

Substituting values from individual fits gives:

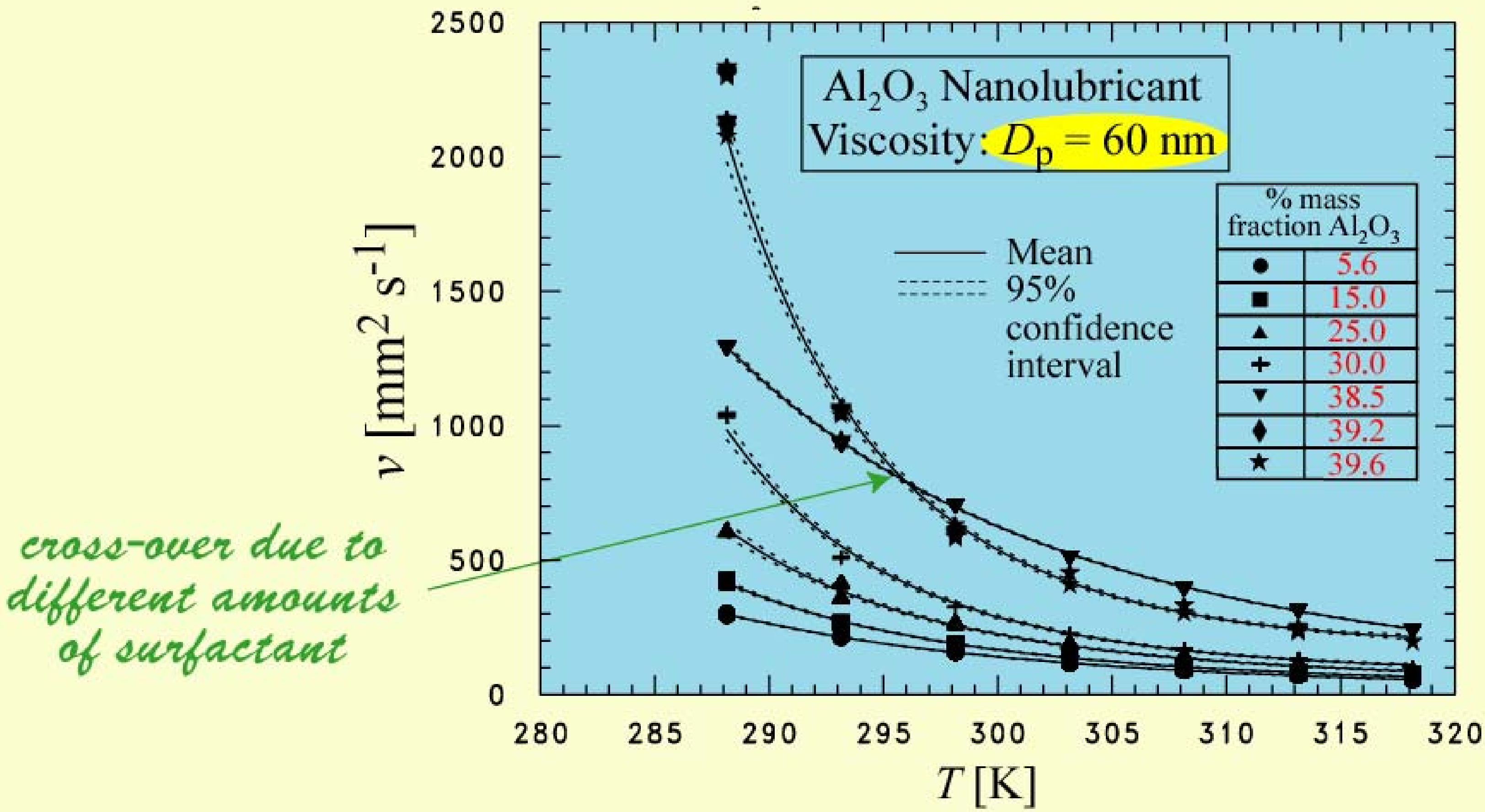
$$\frac{1}{\rho_{\mathrm{m}}}[\mathrm{kg}^{-1}\cdot\mathrm{m}^{3}] = \left(7.647\times10^{-7}(1-x_{\mathrm{np}}) - 8.647\times10^{-9}x_{s}\right)T\,[\mathrm{K}] + 7.979\times10^{-4} - 5.201\times10^{4}x_{\mathrm{np}} + 4.640\times10^{-5}x_{s}$$

Viscosity of Nanolubricant for Several Al_2O_3 Mass Fractions



Larger uncertainties for larger mass fractions

Viscosity of Nanolubricant for Several Al_2O_3 Mass Fractions



Nanoparticle size does affect the viscosity

Normalized viscosity fitted to normalized temperature

$$\frac{\nu}{\nu_0} = \exp\left(A_0 + \frac{A_1}{T_r} + A_2 \ln(T_r) + A_3 T_r^{A_4}\right)$$

not significant

$\nu_o = 1\ mm^2 \cdot s^{-1}$

$T_r = T/273.15\ K$

x_{np}	x_s	x_L	D_p (nm)	U_v (%)	Fitted Constant			Residual standard deviation of fit (%)
					A_0	A_1	A_2	
0	0	1.0	N/A	2.1	-52.1912	58.8418	36.8165	1.0
5.6	0.014	0.930	10	7.5	-69.7768	76.7281	52.0952	3.8
5.6	0.011	0.933	60	2.7	-60.8428	67.7102	44.1411	1.3
15.0	0.038	0.812	10	3.6	-146.202	154.079	119.893	1.8
15.0	0.030	0.820	60	4.2	-147.872	155.481	121.854	2.1
25.0	0.062	0.688	10	14.6	-358.951	368.915	309.006	7.4
25.0	0.050	0.700	60	12.8	-194.279	202.522	163.128	6.5
24.8	0.078	0.674	10	9.6	-237.389	246.384	201.732	4.8
24.4	0.091	0.665	10	2.7	-113.035	121.208	91.3062	1.3
30.0	0.060	0.640	60	9.8	-302.099	311.362	258.869	4.9
39.6	0.079	0.525	60	14.0	-386.581	396.955	335.349	7.1
39.2	0.098	0.510	60	1.7	-68.7064	76.9815	52.4197	0.8
38.5	0.115	0.500	60	2.5	-36.9608	45.1948	23.9985	1.2
0	0.500	0.500	N/A	4.8	-246.727	257.904	208.615	2.4

residuals for the fits are within 8 % for all of the fluids

Model for Nanolubricant Viscosity

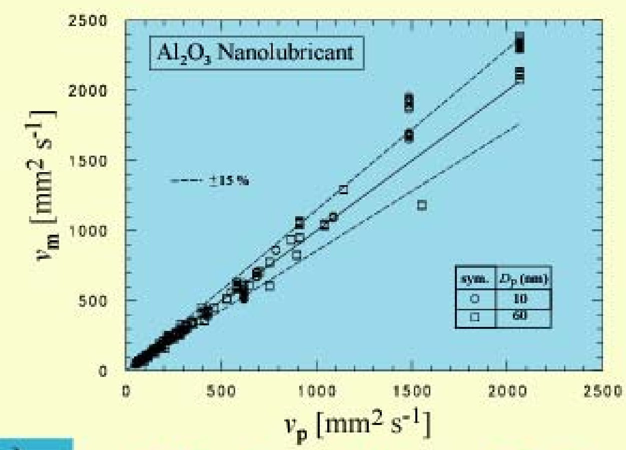
General mixing rule:

$$\ln v_{\mathrm{m}} = x_{\mathrm{L}}^{1.25} \ln v_{\mathrm{L}} + x_{\mathrm{np}}^{1.25} \ln v_{\mathrm{np}} + x_{\mathrm{s}}^{1.25} \ln v_{\mathrm{s}}$$

exponent changed from 1 to 1.25 for improved fit

Pseudo-surfactant viscosity:

$$\ln v_{\mathrm{s}} = 0.149 D_{\mathrm{np}}[\mathrm{nm}] - 87.2079 + \frac{7.1353}{T_{\mathrm{r}}^{-66.12} + 0.074}$$



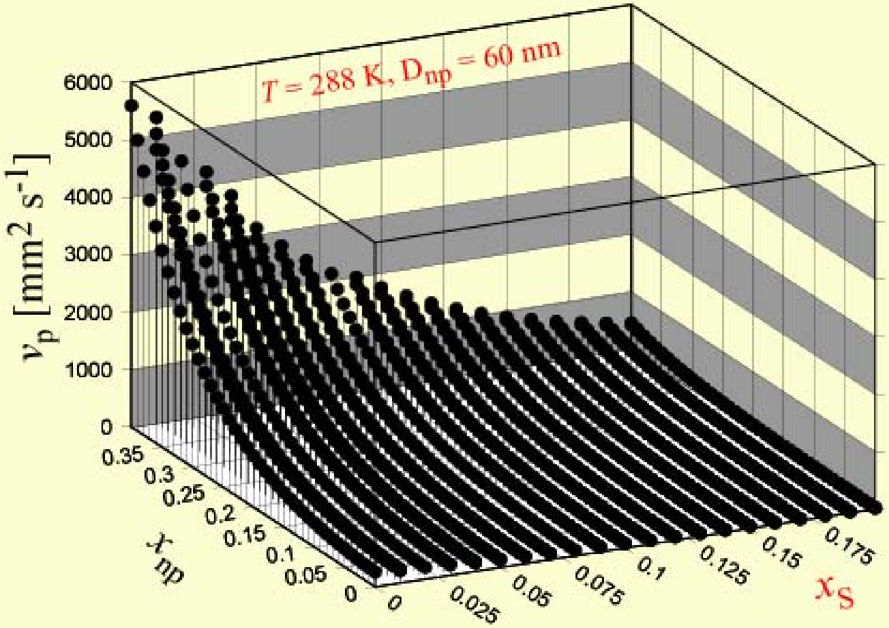
95 % within 15 %

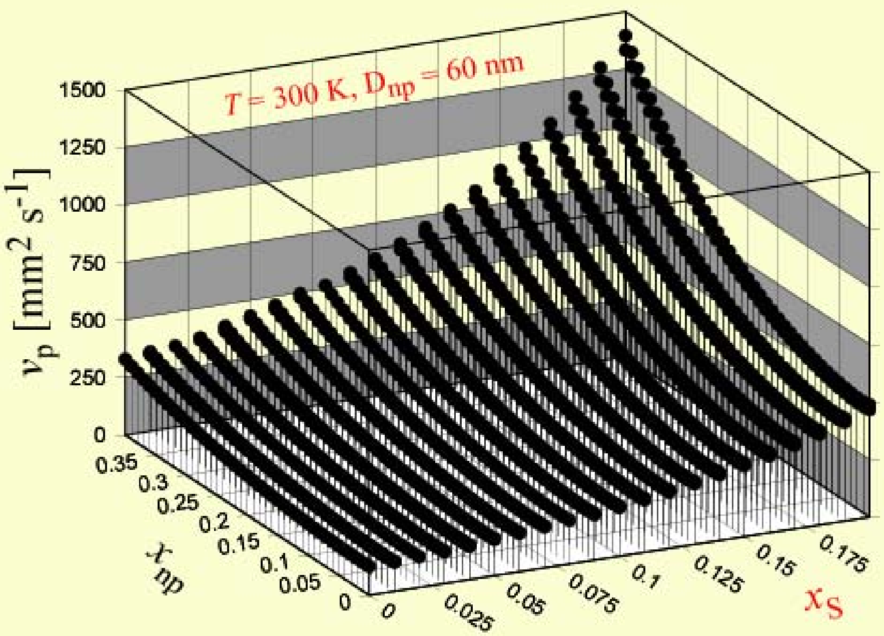
Pseudo-nanoparticle viscosity:

$$\ln v_{\mathrm{np}} = \left(1.426 - 0.0071 D_{\mathrm{np}}[\mathrm{nm}]\right)\left(4.7356 + \frac{1.4706}{T_{\mathrm{r}}^{4.05} - 1.11}\right)$$

Nanoparticle diameter term accounts for the interaction between the nanoparticle and the surfactant

Effect of Temperature and Surfactant Mass Fraction on Viscosity





Between 300 K and 318 K , increase in x_S causes an increase in viscosity, while the opposite is true for temperatures between 288 K and 300 K

Boiling Conclusions

Conclusions Plain Surface

- In general, nanoparticles can be used to produce significant enhancement relative to the heat transfer of pure R134a/polyolester
- However, the choice of the nanoparticle material, size, and concentration is critical in order to achieve a sustained and significant enhancement
- A high quality nanolubricant dispersion is essential for obtaining a boiling enhancement via momentum transfer from nanoparticles to bubbles.
- A bad dispersion can give an boiling enhancement via increase viscosity, but it is short-lived.
- The thermal conductivity of the nanoparticle does not play a large role in the boiling heat transfer enhancement.

Conclusions Plain Surface (cont.)

- A semi-empirical model is now available to predict the enhancement of refrigerant/lubricant pool boiling by assuming that the transfer of momentum from the nanoparticles to the bubbles is responsible for the boiling enhancement
- For heat fluxes greater than 20 kW/m2, the model underpredicted the (99.5/0.5), the (99/1), and the (98/2) mixtures on average by approximately 25 %, 0.2 %, and 6 %, respectively.
- The model predicts that the maximum performance is approached for volume fraction and mass fractions nearing unity, and forever decreasing nanoparticle size.
- Future research is required to validate the model beyond the range of parameters investigated here.

Conclusions: Reentrant Cavity

- Al_2O_3 nanoparticles caused, on average, a 12 % degradation in the boiling heat transfer relative to that for R134a/polyolester mixtures without nanoparticles for the three lubricant mass fractions that were tested.

- It was speculated that the degradation resulted from nucleation being less important and suppressed for reentrant cavity boiling and increased surface wetting (reduced contact angle).

Viscosity Conclusions

Conclusions

- Liquid kinematic viscosity and liquid density measurements of a synthetic polyolester based aluminum oxide (Al_2O_3) nanoparticle dispersion (nanolubricant) have been presented at atmospheric pressure and for a temperature range from 288 K to 318 K.

- Viscosity and density measurements were made for the pure base lubricant along with twelve nanolubricants with differing nanoparticle mass fractions.

- The liquid kinematic viscosity was correlated with respect to temperature, nanoparticle mass fraction, surfactant mass fraction, and nanoparticle diameter.

Conclusions (cont.)

- Pseudo-viscosities were developed to account for the interaction between the nanoparticle and the surfactant.
- A linear relationship was developed for liquid specific volume with respect to temperature
- Both the liquid density and the viscosity decreased with respect to temperature and increased with respect to the Al_2O_3 nanoparticle mass fraction
- Depending on the temperature, the surfactant caused the viscosity to either increased or decrease with respect to x_s
- The measurements are important for the design of nanolubricants for heat transfer and flow applications