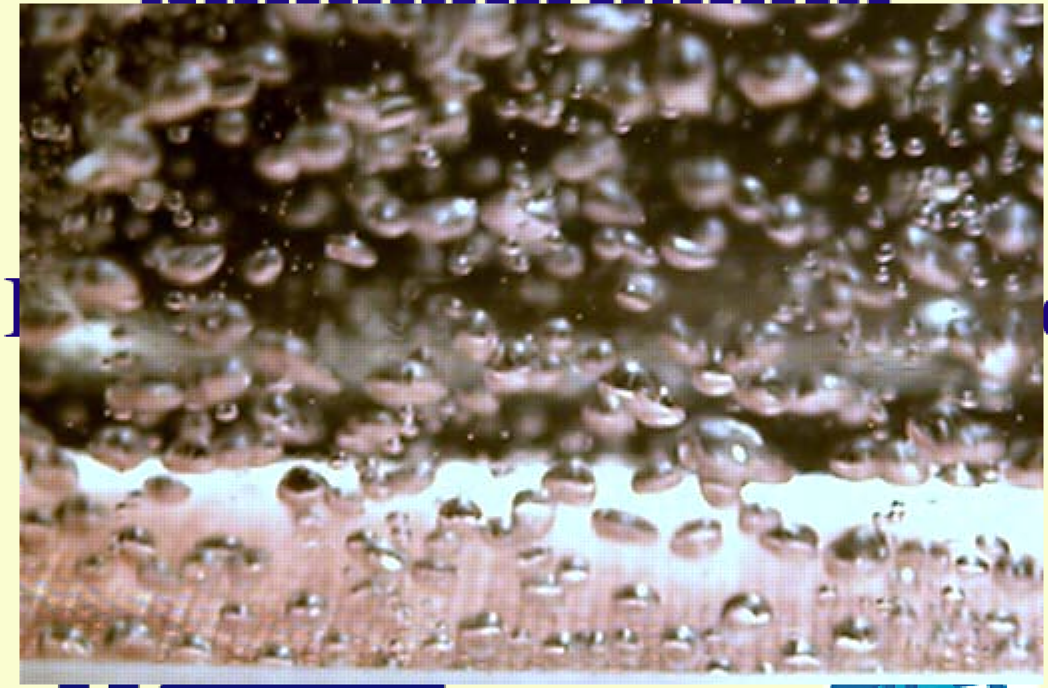
Boiling with Refrigerants and Nanolubricants

Mark A. Kedzierski
National Institute of Standards and Technology
Gaithersburg, Maryland

Boiling with Refrigerants and Nanolubricants



National I chnology

Learning Objectives

Nanoparticle Basics

Review of Some Key Measurement Results

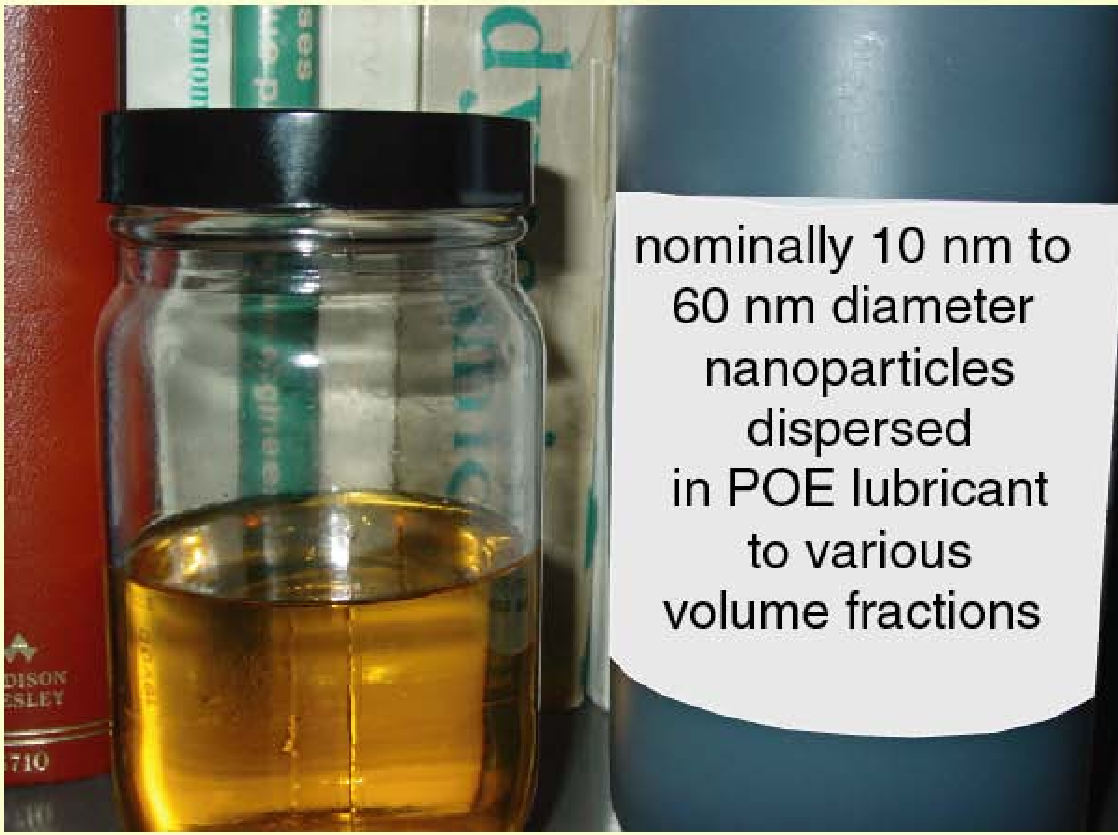
....with Mechanistic Speculation

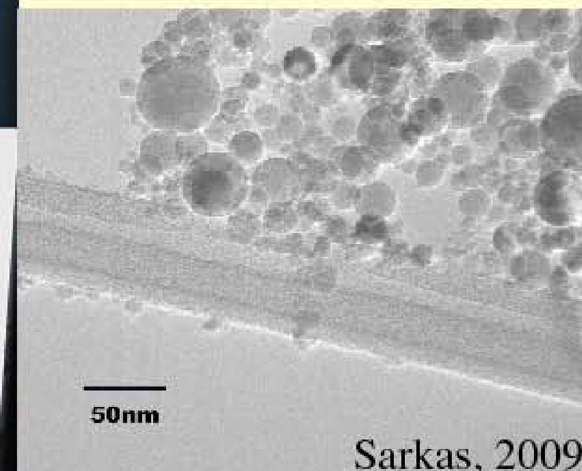
Boiling Model

Conclusions (review)

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



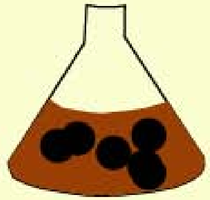


Nanoparticles Can Improve Refrigerant/Lubricant Boiling

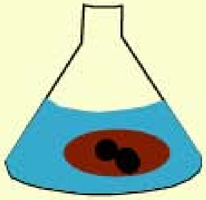
But this depends on the:

Properties of the nanoparticles:

Concentration of nanoparticles in nanolubricant:

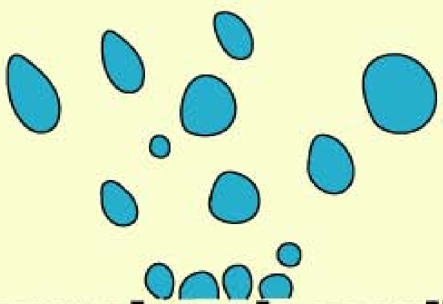


Concentration of nanolubricant in refrigerant:



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

$$\frac{q''_{np}}{q''_{PL}} = 1 + \frac{3.45\times10^{-9}[\mathrm{s}]\,\phi\,\sigma\,\nu_{L}\,\rho_{v}\,x_{b}^{2}}{D_{np}^{4}\left(q''_{n}\right)^{3/2}\rho_{L}\left(\rho_{np}-\rho_{L}\right)g\left(1-x_{b}\right)^{2}}$$

pure refrigerant properties

nanoparticle volume fraction

nanolubricant mass fraction

nanoparticle properties

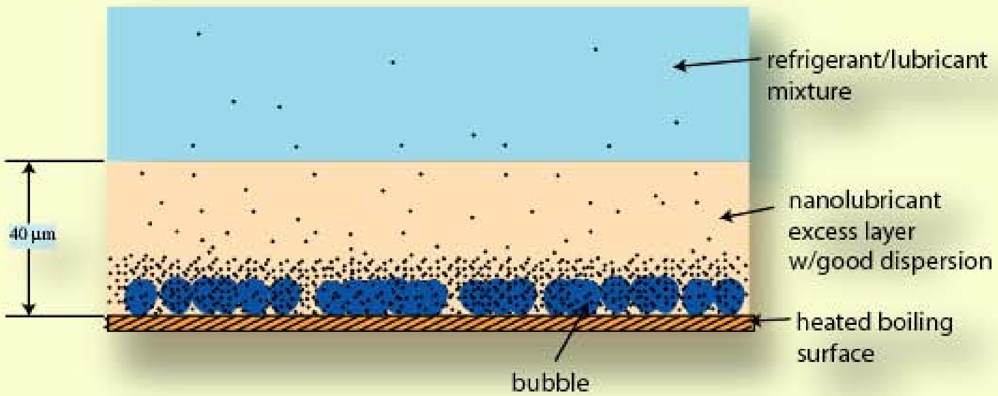
pure lubricant properties

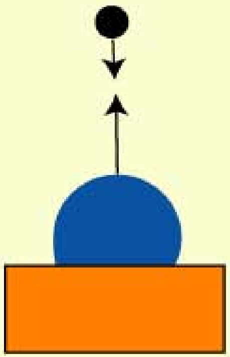
refrigerant/nanolubricant heat flux

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

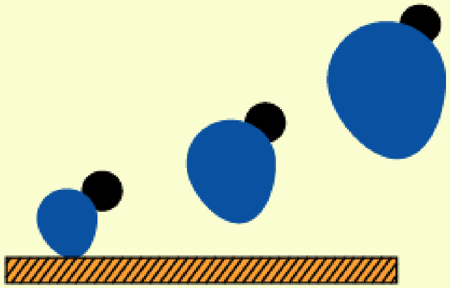
$$\frac{N_{\mathrm{np}}}{N_{\mathrm{b}}} M_{\mathrm{np}} u_{\mathrm{np_i}} + M_{\mathrm{b_i}} u_{\mathrm{b_i}} = \frac{N_{\mathrm{np}}}{N_{\mathrm{b}}} M_{\mathrm{np}} u_{\mathrm{np}} + M_{\mathrm{b_f}} u_{\mathrm{b_f}}$$

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

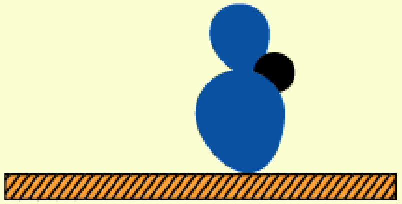
$$\frac{1}{2} M_{\mathrm{np}} u^2_{\mathrm{np_f}} - \frac{1}{2} M_{\mathrm{np}} u^2_{\mathrm{np}} = 4\pi\sigma\left(r^2_{\mathrm{b_f}} - r^2_{\mathrm{b_i}}\right)$$

Proposed Enhancement Mechanism

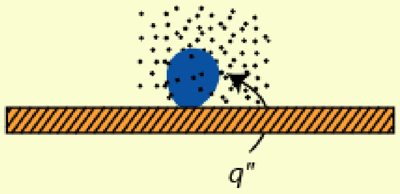
enhanced bubble growth caused by bubble/ "hot" particle interation



secondary nucleation on "hot" partical in fluid



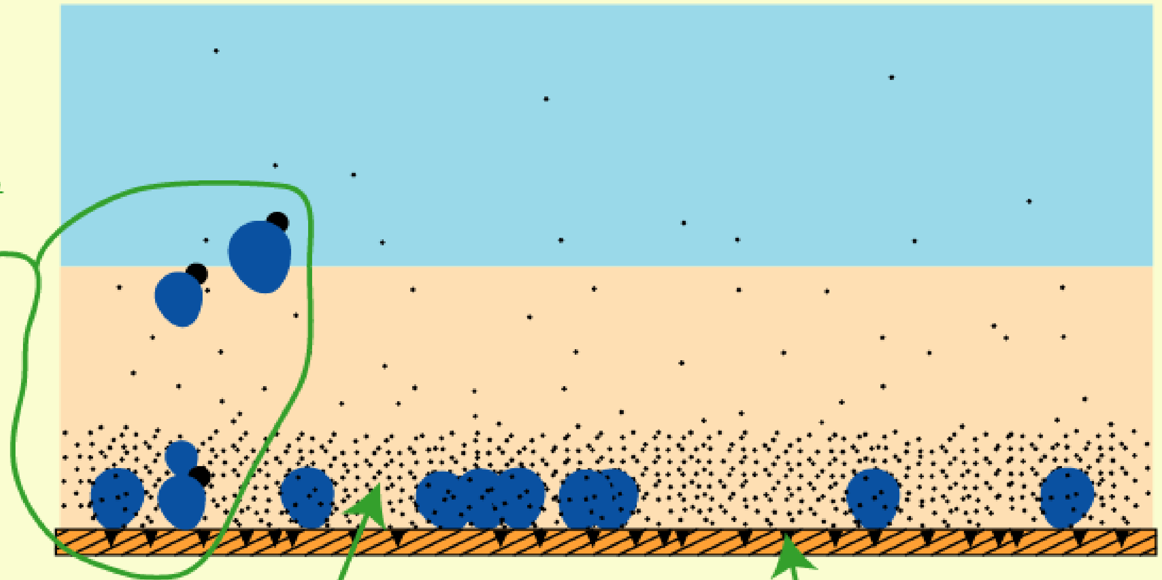
particle momentum transfer to bubbles



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:

(1) boiling enhancement via nanoparticle interaction with bubbles (primarily momentum transfer effects)

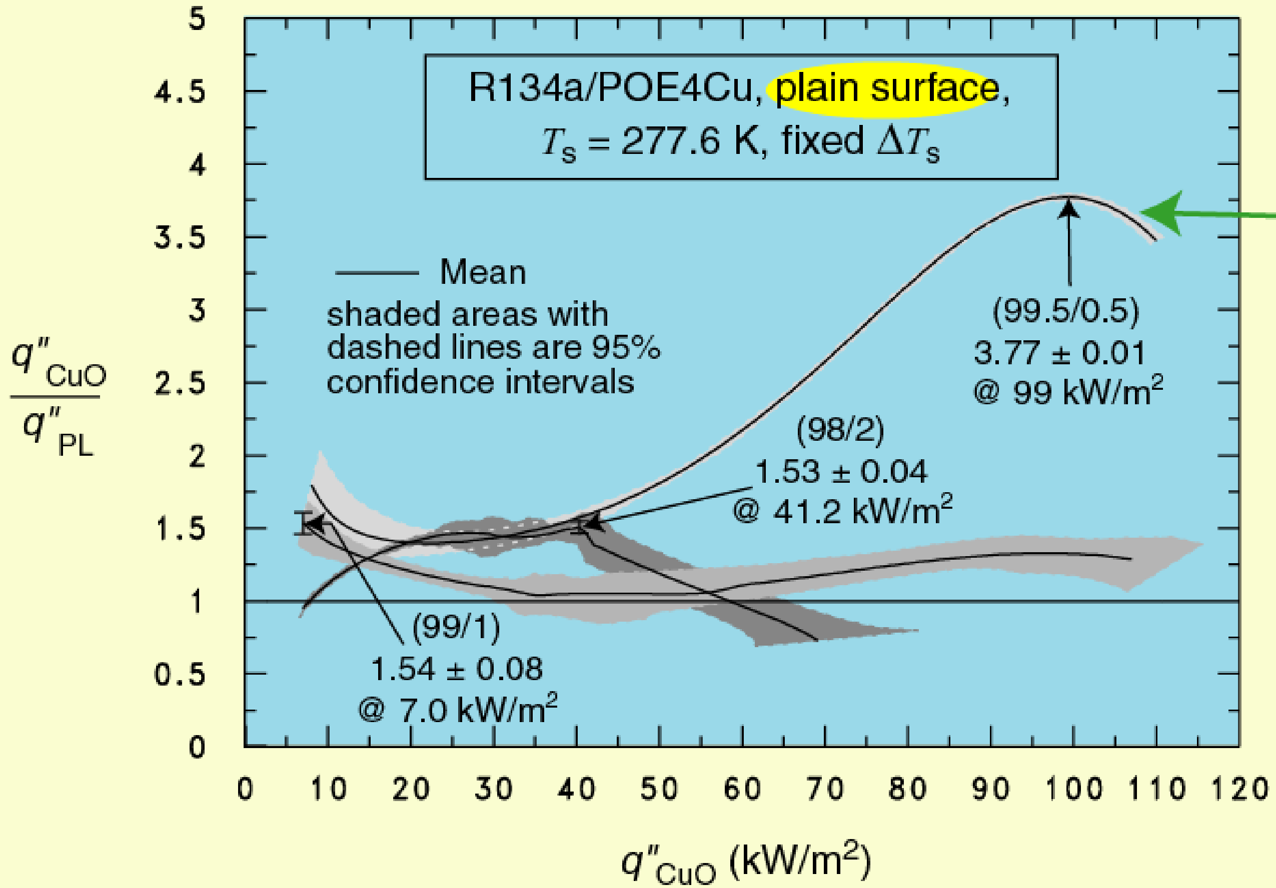


(2) improved thermal conductivity of lubricant excess layer by the accumulation of highly conductive nanoparticles

(3) loss of nanosize nucleation sites due to nanoparticle filling of cavities.

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

Effect of 4% Vol. Fraction CuO Nanoparticles on Boiling



0.5% mixture is roughly between 1.5 and 3.75

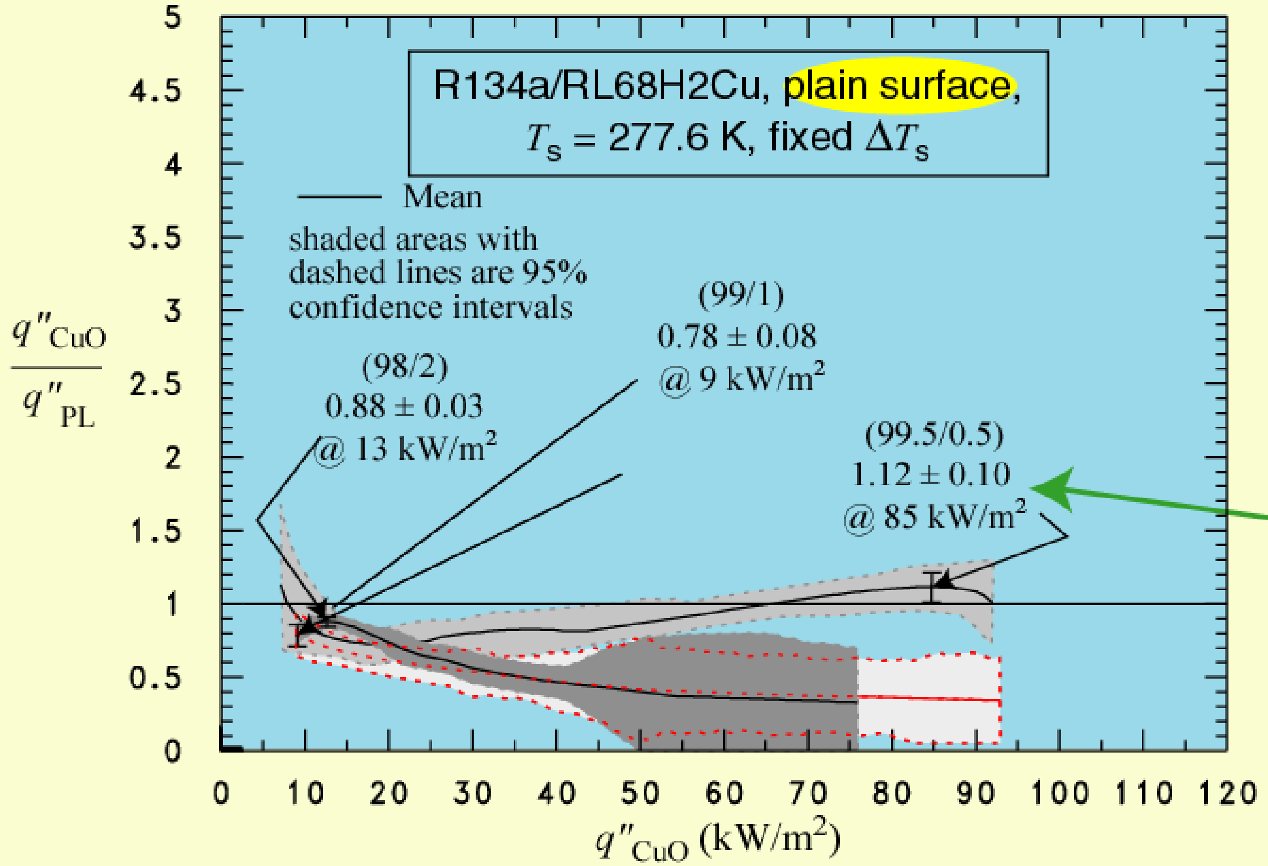
Average ratio:

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

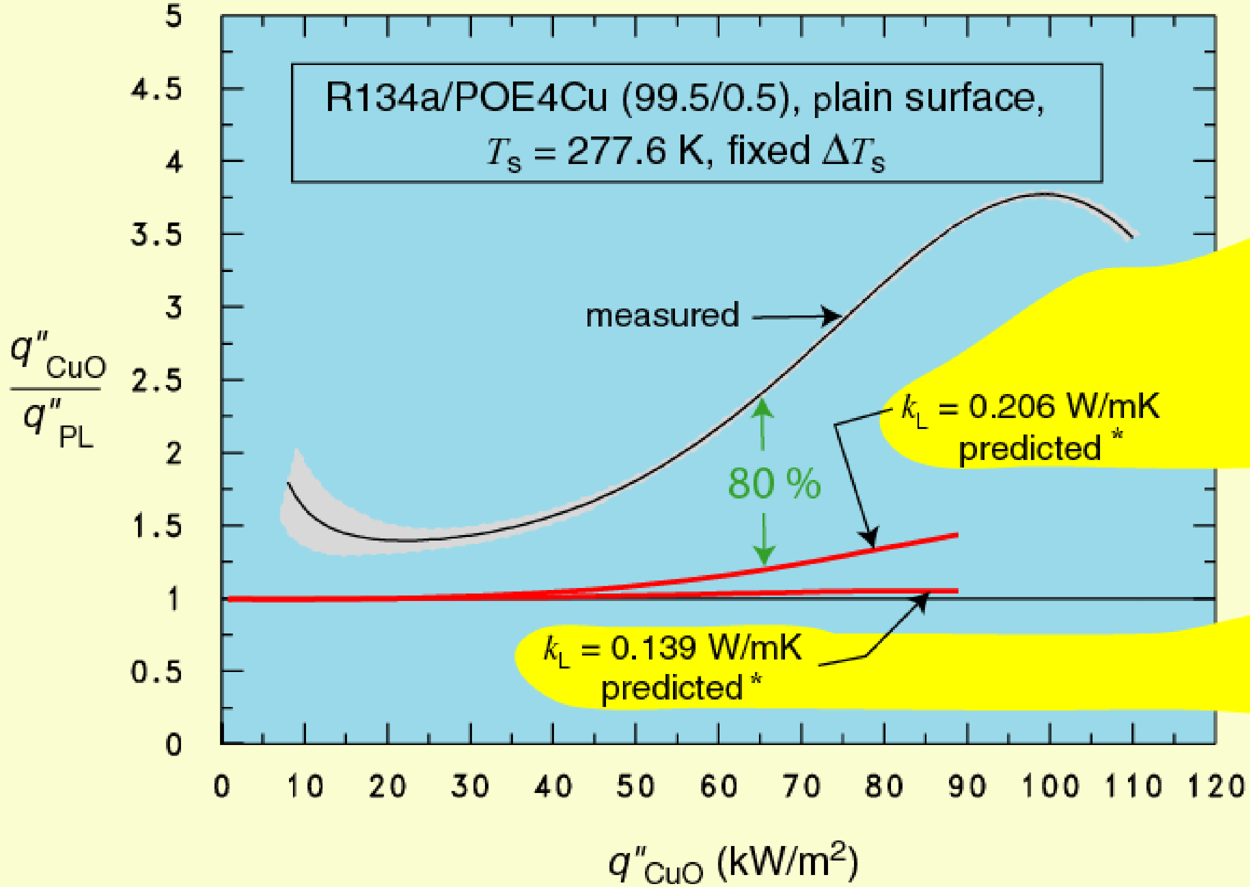
1% → 0.4

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

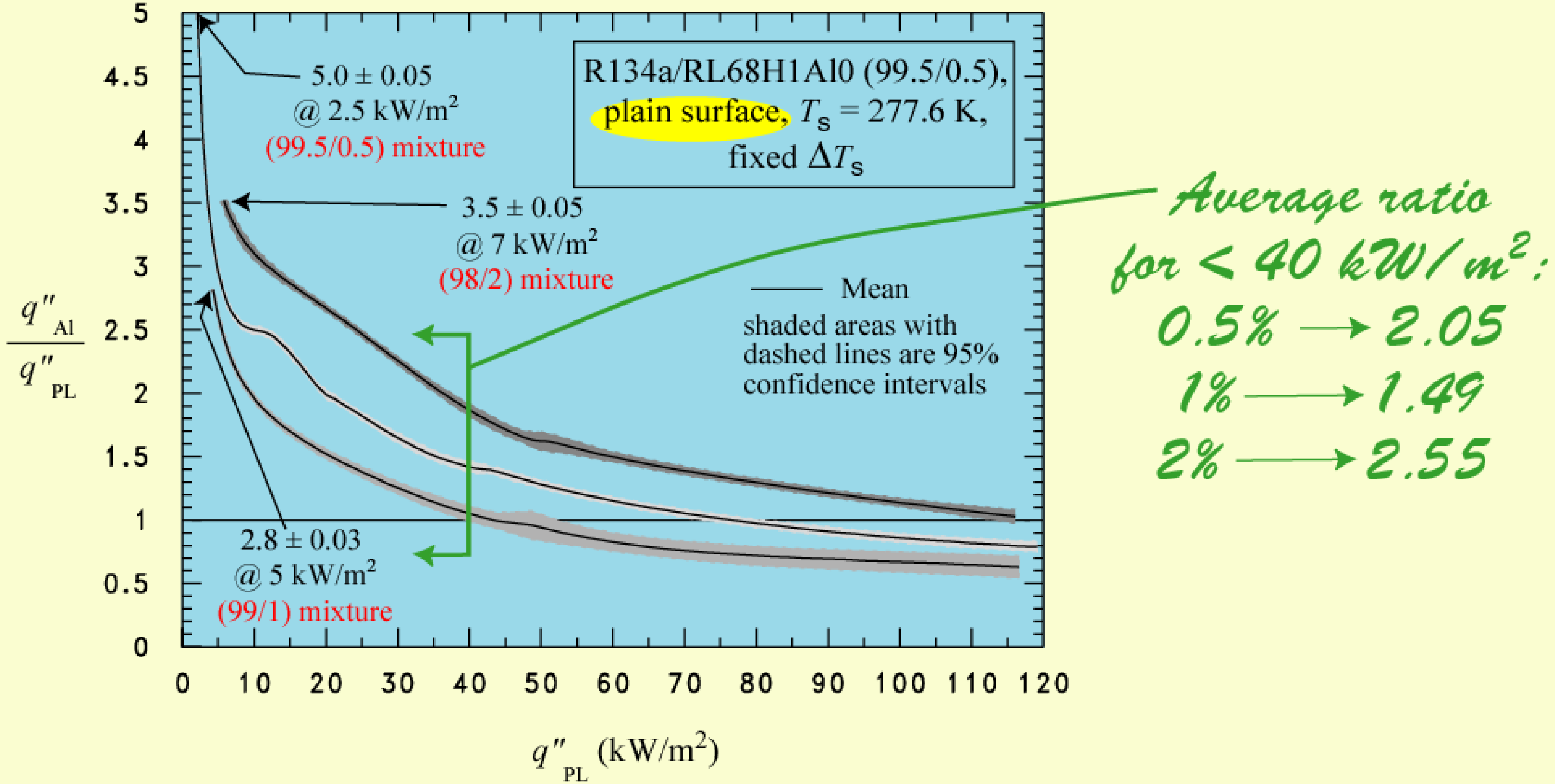


Approx 20 % of the enhancement may be due to increased thermal conductivity

* Refrigerant/lubricant pool boiling model Kedzierski 2003 ICR

Effect of Al_2O_3 Nanolubricant on R134a Boiling

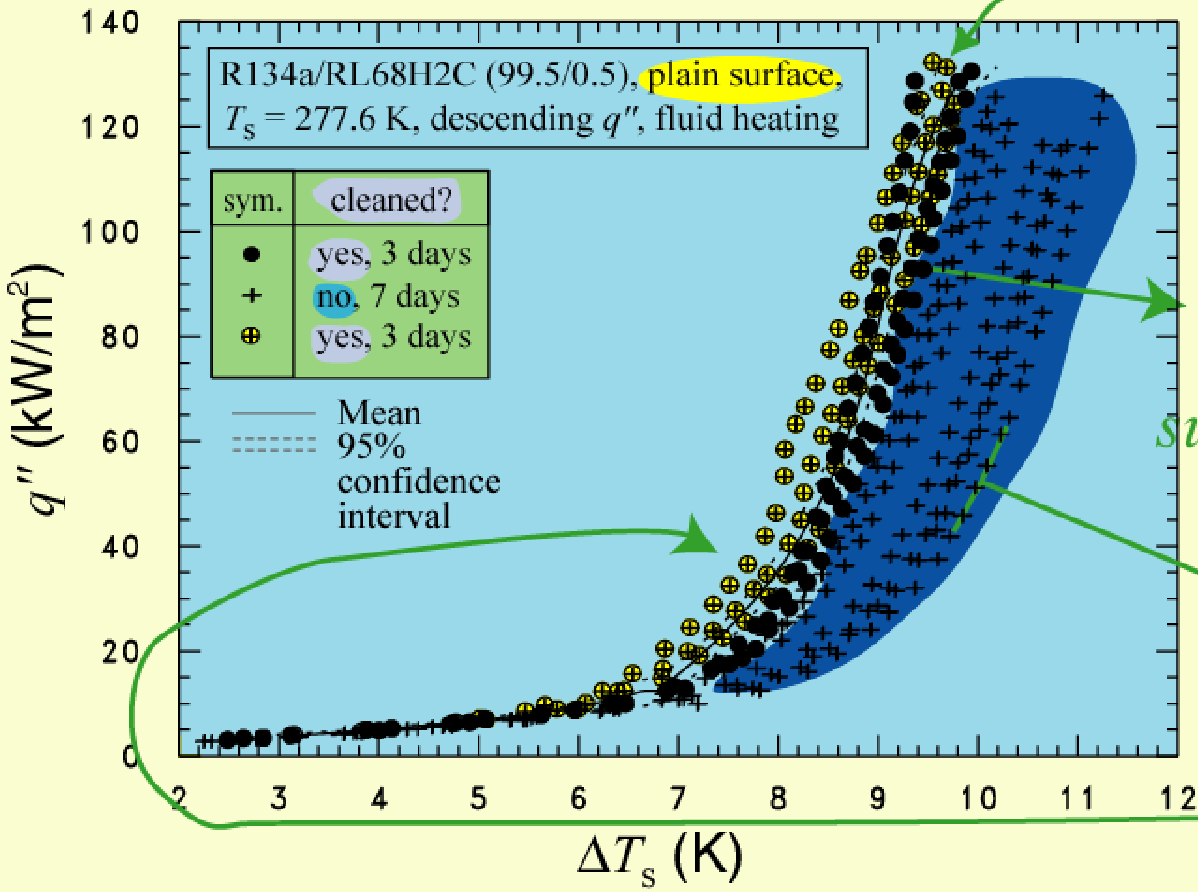
Aluminum oxide nanoparticles provided the most favorable benefit to the 2 % mass fraction mixture



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

Effect of Particle Agglomeration on R134a/Diamond Nanolubricant boiling

cleaned/new test surface

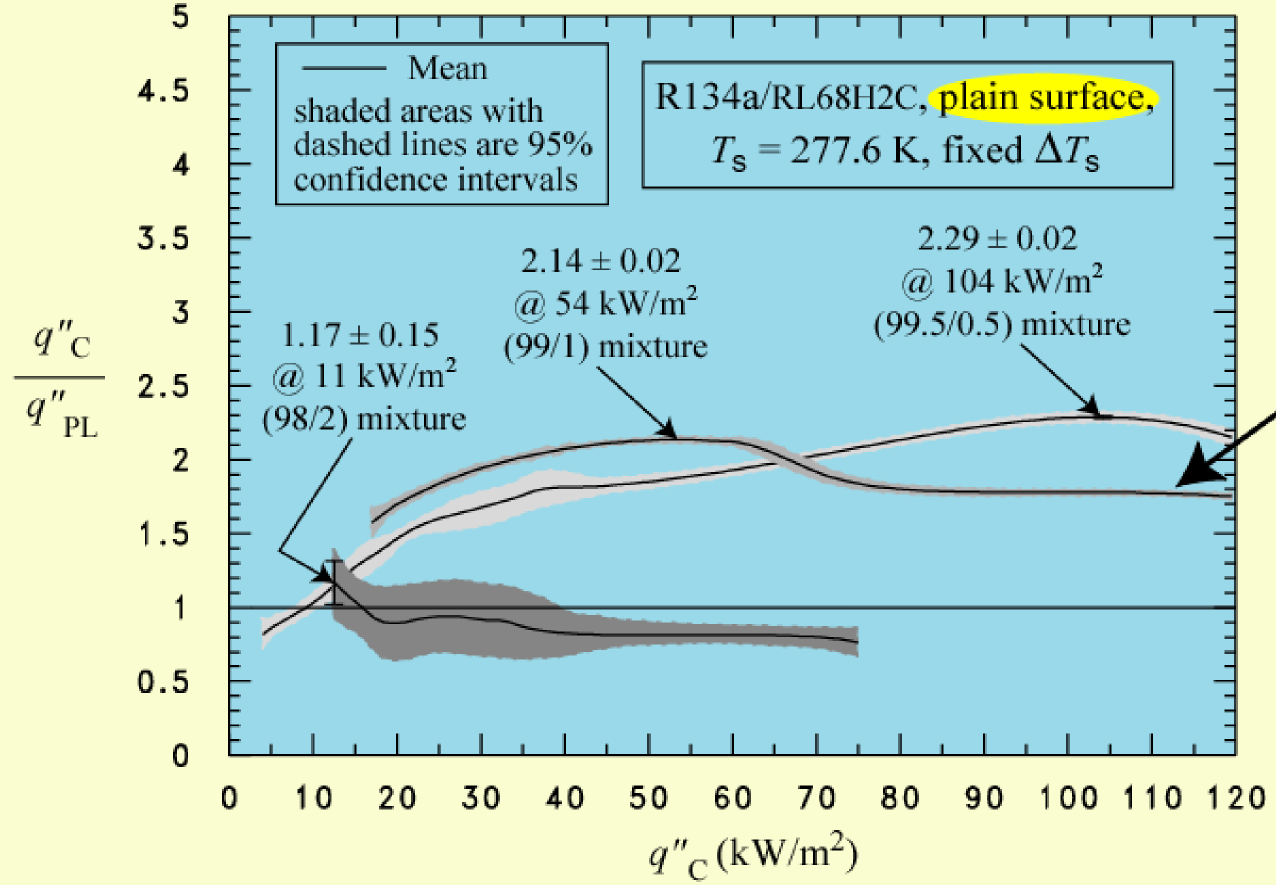


increasing particle agglomeration on surface after each day

cleaning restores the performance

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

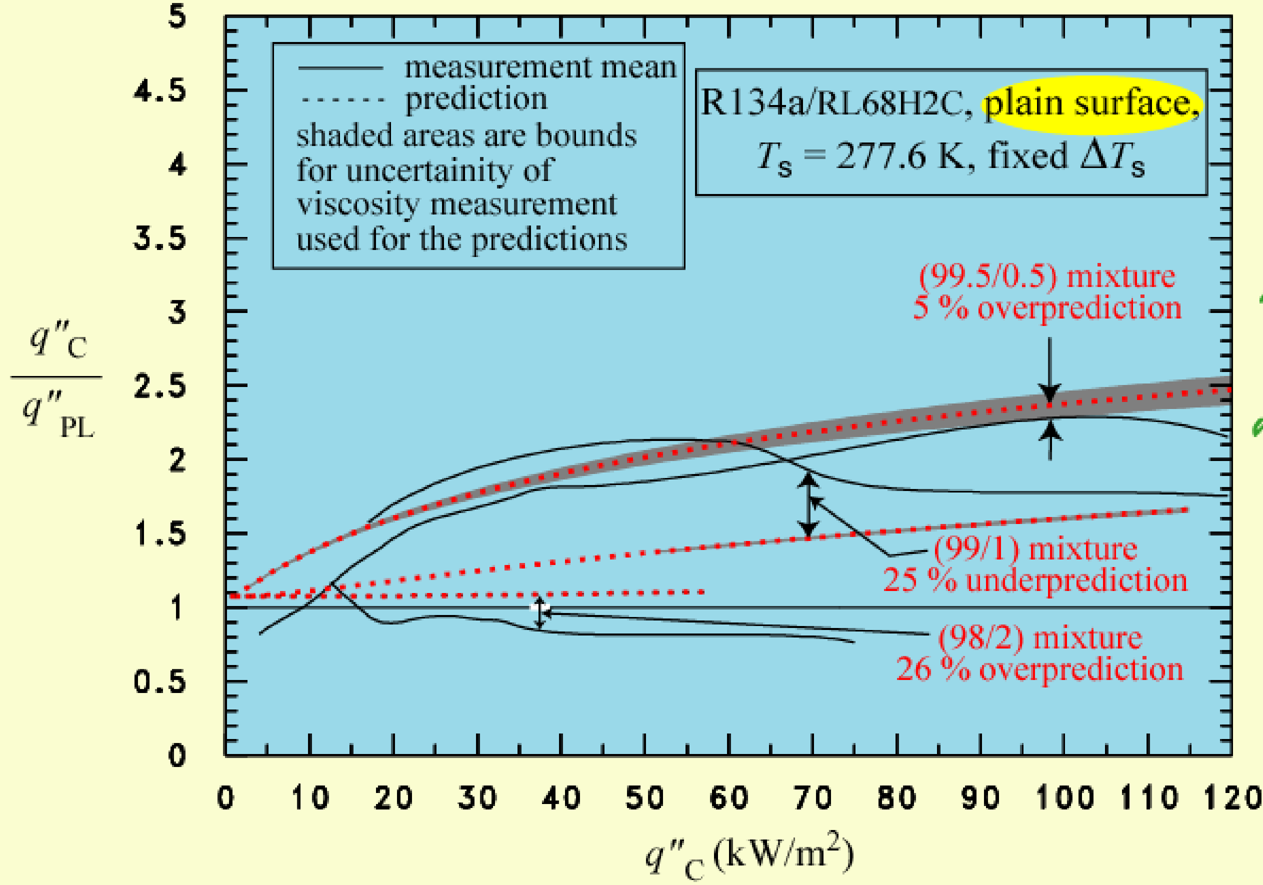
1% → 1.91

2% → 0.81

Sustainable improvement for wide heat flux range

Increased Viscosity Caused Enhancement (not particle interaction)

kinematic viscosity increased by 550%

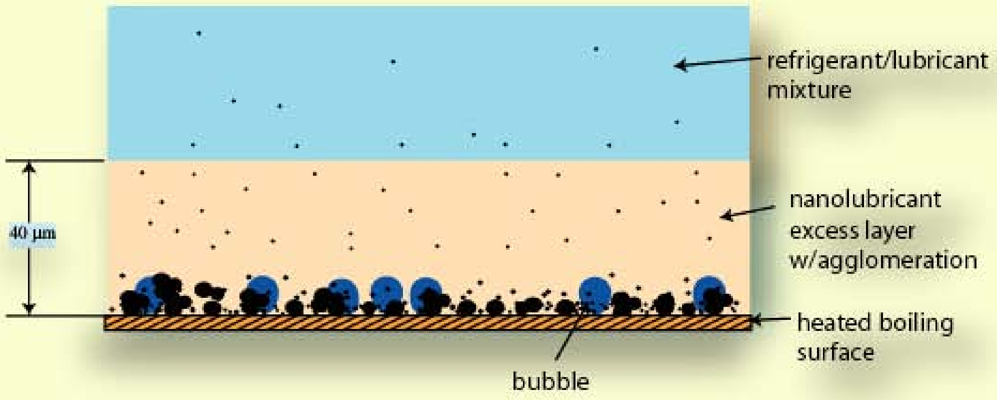


Model can predict only property effects, not nanoparticle interaction with bubbles

Refrigerant/lubricant boiling model predicts enhancement based on viscosity increase

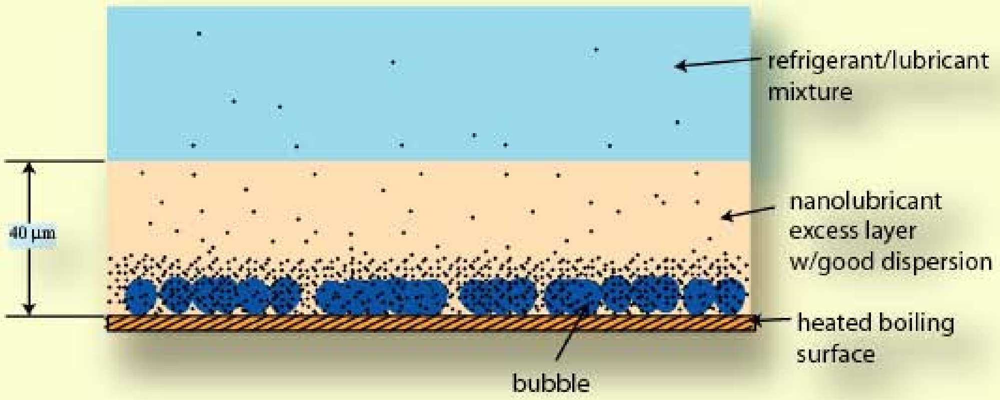
*Refrigerant/lubricant pool boiling model Kedzierski IJR 2003

Particle Interaction with Bubbles Depends on the Quality of the Dispersion



Bad Dispersion

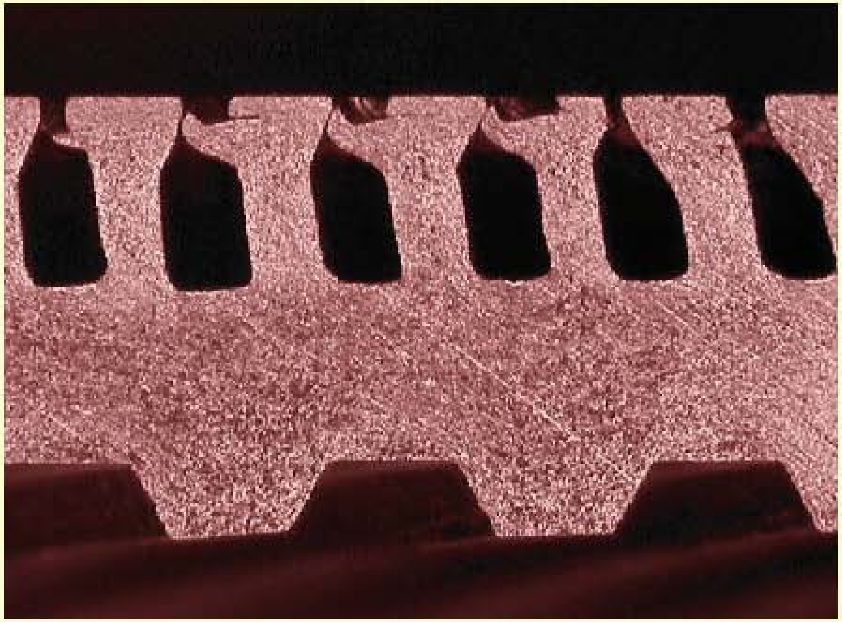
Particles don't remain suspended in excess layer



Good Dispersion

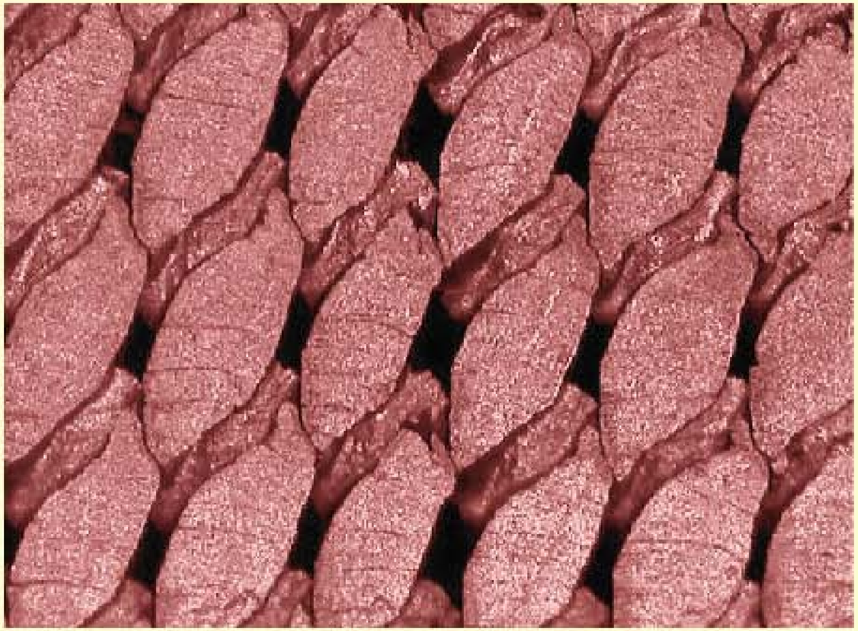
Particles remain suspended to interact with bubbles

Photograph of
Reentrant Cavity Boiling Surface



– 0.1 mm

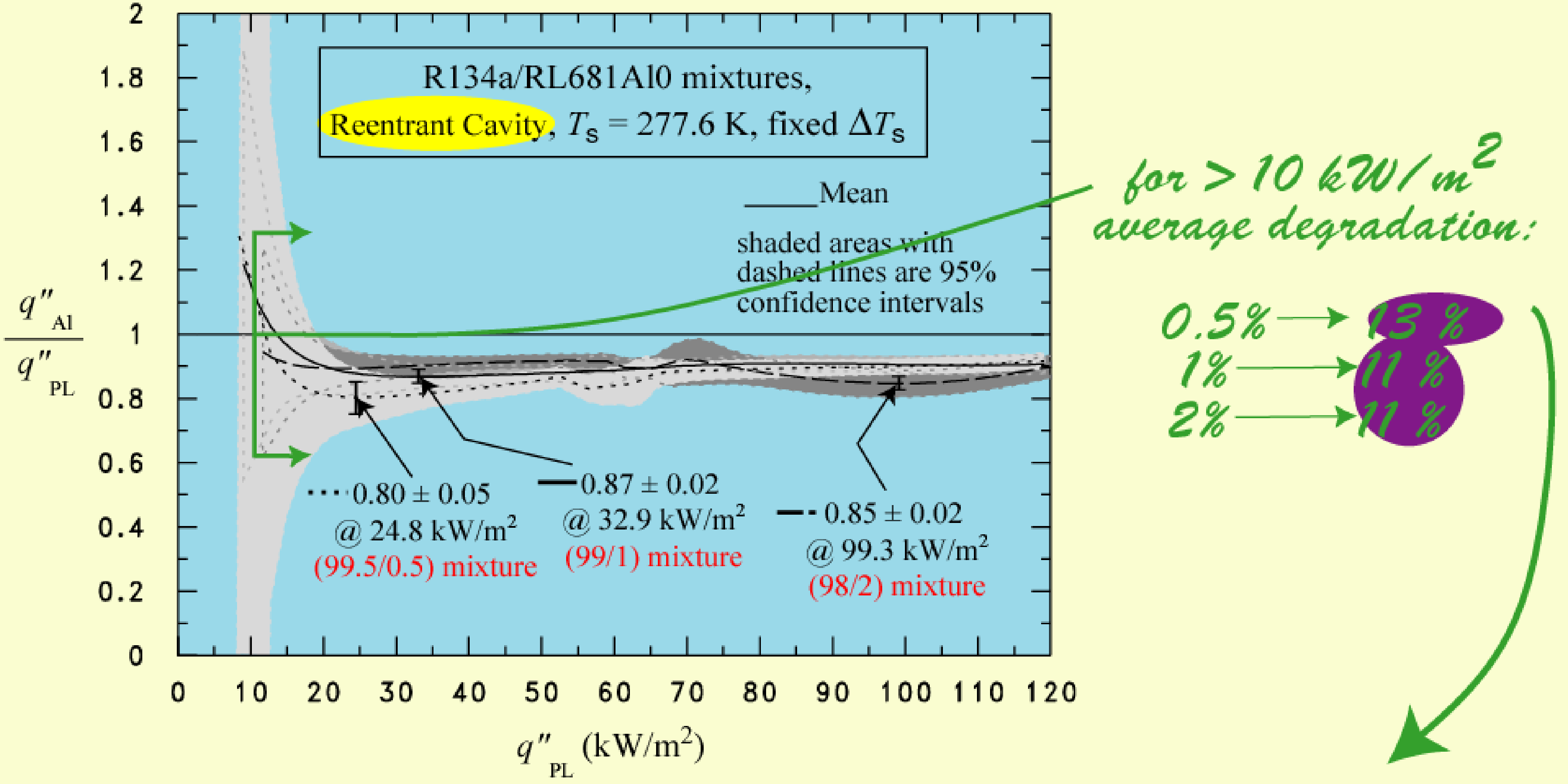
SIDE VIEW



– 0.1 mm

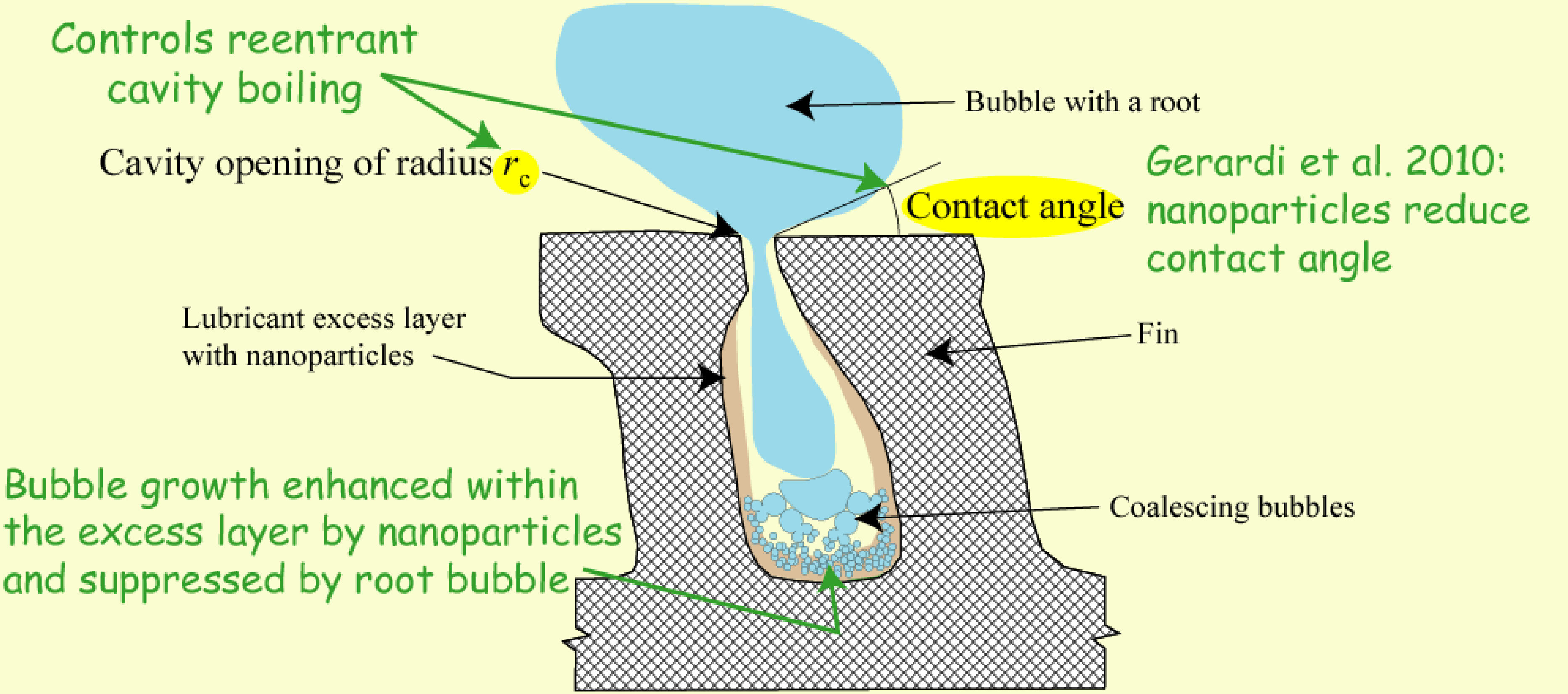
TOP VIEW

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

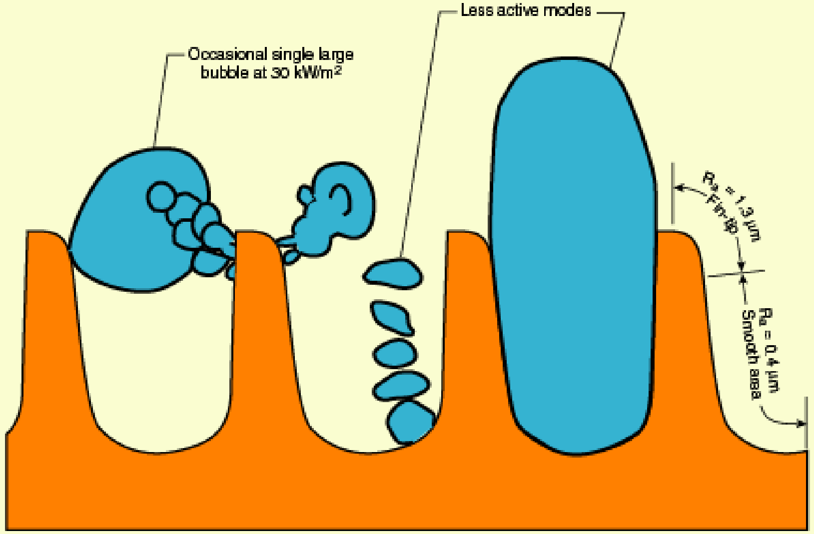


Positive effect of nanoparticles reduced because bubble nucleation in cavity less important and suppressed

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

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).