Influence of lubricant on the heat transfer performance of refrigerant – a review

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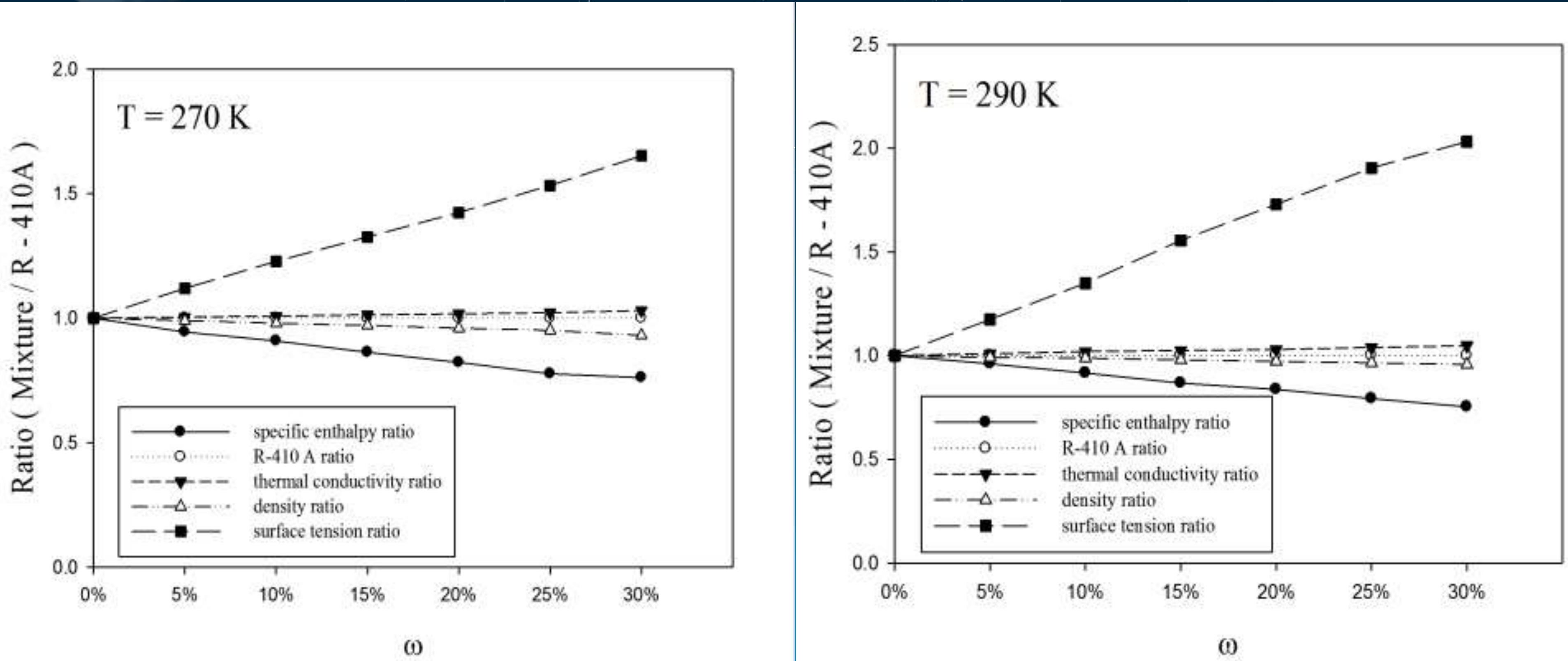
Introduction for Lubricant oil

- For vapor compression processes
  - in a refrigerating or heat pump system is very essential for lubricating
  - sealing the sliding parts
  - cushioning cylinder valves
- As a coolant in compressor
  - transferring heat from bearings and mechanical elements to the crankcase sum
  - relieves the generated noise from the moving part

- air-conditioning or refrigeration system
  - small amount of lubricant oil may migrate from the compressor and into another part of the system
  - altering the heat transfer and frictional characteristics of the refrigerant

The presence of lubricant..

- Affect the thermodynamic and transport properties of refrigerant
  - viscosity
    - about two to three orders higher than that of refrigerant
  - surface tension
    - approximately one order higher than that of refrigerant
- Casting a significant impact on the heat transfer characteristics



Schematic of the associated properties of R-410A/POE VG68 mixture based on the calculated results.

Wei et al. [1]

Background of Lubricant oil

- According to ASHRAE [2] classification, The mineral oils can be subdivided into
  - paraffins, naphthenics, aromatics and non-hydrocarbons
- When the HFCs were proposed as substitutes of CFCs
  - the synthetic oils had been introduced for the widely used mineral oils are not miscible
- The synthetic lubricant oils are classified as
  - Polyol Ester (POE), Poly Aklylene Glycol (PAG), Alkyl Benzene (AB), Poly Alpha Olefin (PAO).

- Some additives provide performance advantages in one area but could raise other problems in another.
- The presence of these additives further complicate the heat transfer performance of the lubricant oils.

Effect of lubricant on the heat transfer of conventional refrigerants

Effect of Lubricant on Pool Boiling

- The effect of lubricant on heat transfer is rather small at a low weight concentration, i.e. $\omega < 3\%$, and for $2\% < \omega < 4\%$.
- Some types of lubricant can enhance the pool boiling, and with a higher concentration ($\omega > 5\ \%$).
- Almost all types of lubricant oil reduce pool boiling heat transfer.

Zheng et al. [13]

- Conducted boiling of ammonia/lubricant mixture on a flooded evaporator with inlet quality @ a saturation temperature of 7.2 °C
  - adding lubricant up to 5% concentration
    - the heat transfer coefficient (HTC) is decreased
  - from 5% to 10%
    - a significant increase of HTC
- However, this phenomenon is not seen at an elevated saturation temperature of 23.3 °C
  - x_{in} = 0.2 and x_{in} = 0.4 at T_s = -9.4 °C.

Wang et al. [14]

- Investigated the effect of lubricant oil (3GS) on the pool boiling heat transfer performance for plain tube
  - saturation temperatures of 20 °C, 4.4 °C, and -5 °C
  - oil concentrations of 0.75, 1.5, 3.6, and 7%

- For T_s = 20 °C
  - the HTC is decreased with rise of oil concentration.
  - For q = 21.1 kW/m^2
    - the heat transfer coefficients for ω = 3.6% is about 55% that of pure refrigerant while for ω = 7%
    - the heat transfer coefficient is only 45% of pure refrigerants.

- For T_s = 4.4 °C
  - the effect of lubricant on HTC becomes less profound
  - there is no significant decrease of heat transfer coefficients for $\omega < 2\%$
- For T_s = -5 °C
  - the effect of lubricant oil on HTC is reversed
  - The heat transfer coefficients with oils are higher than those of pure refrigerants over the range of ω = 0~3%.
  - A maximum increase of 20~30% of heat transfer coefficient is observed near ω = 1.5%.

Effect of physical property

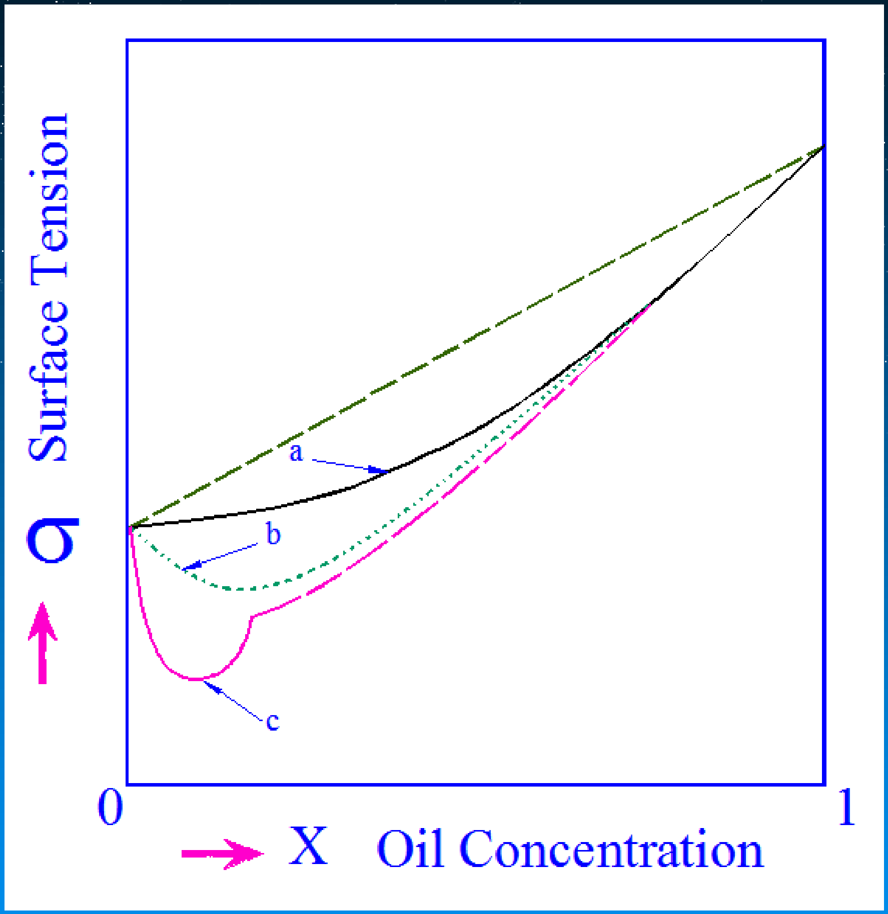
- In an investigation of the surface tension of the refrigerant-oil mixtures
  - the heat transfer coefficients for refrigerant-oil mixtures are strongly related to the interfacial effects

Waller and Dick [16]

- Based on the theoretical developments
  - a simplified formula for the work required for the generation of vapor in the mixtures, i.e.

$$W = \frac{A\sigma^3}{\left[B - C(y - x)\right]^2}$$

Stephan and Körner [17], Waller and Dick [16]



Possible relationship between surface tension and oil concentration.

- For type a
  - the surface tension vs. oil concentrations for refrigerant-oil mixtures did not show a minimum
- For type b
  - the oils contain surface active agent which leads to minimum in surface tension
- For type c
  - the oils contain surface active agent and additional dirt particles in small concentration

Wallner and Dick [16]

- However, the explanation is unable to explain the aforementioned Zheng et al.'s data [13] showing a sharp rise of heat transfer coefficient.

Effect of blocking

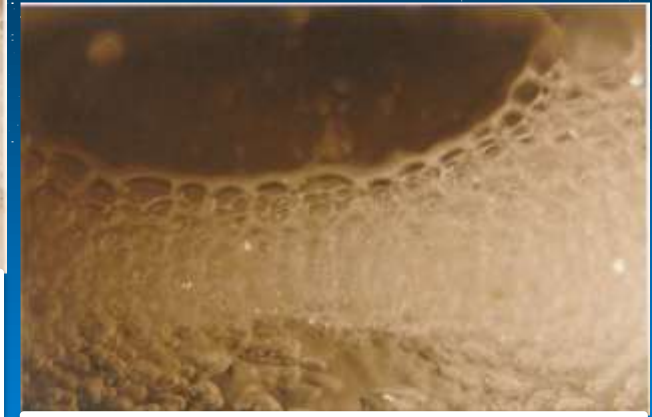
- During evaporation process
  - refrigerant is regarded as the more volatile phase, resulting in an oil enrichment at the phase interface and next to the heating surface.
- For a smaller bubble departure diameter and a higher viscosity of the oil
  - the contribution of convective heat transfer due to bubble motion is lessened

Effect of nucleation site

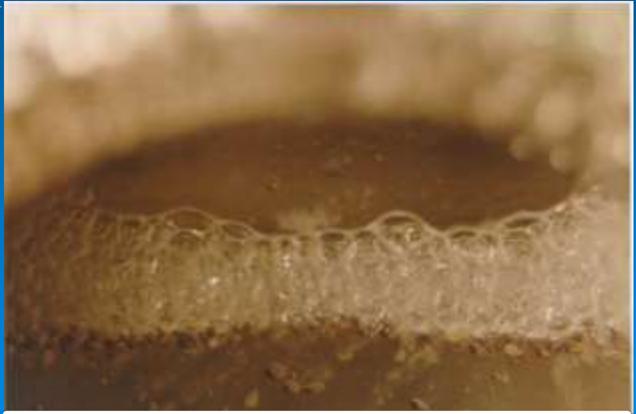
- For refrigerant oil mixtures
  - a higher wall temperature is required to accommodate the same nucleation site density as compared to the pure refrigerant
- The reduced area influenced by one nucleation site can lead to
  - a higher nucleation site density and an increase of the pool boiling heat transfer coefficient

Effect of foaming

q = 84 kW/m^2,
T_S = 20°C,
ω = 0.75%



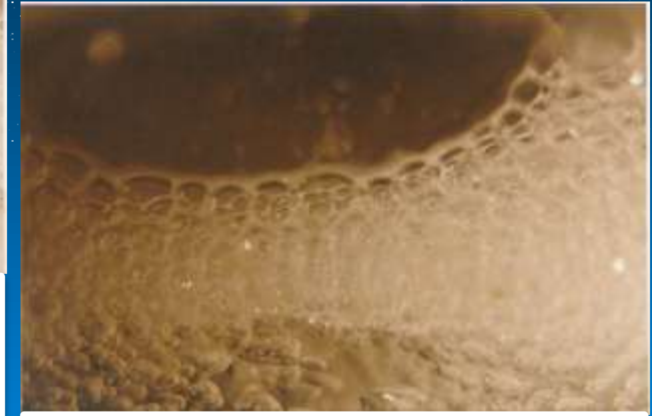
q = 58 kW/m^2,
T_S = 20°C,
ω = 0.75%



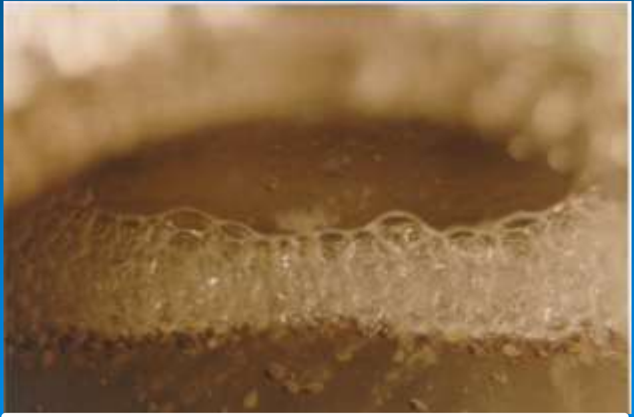
q = 16.7 kW/m^2,
T_S = 20°C,
ω = 0.75%

Boiling pattern for T_s = 20 °C, and ω = 0.75 % [14]

$q = 100.8\ kW/m^2$,
$T_S = -5°C$,
$\omega = 0.75\%$



$q = 50.4\ kW/m^2$,
$T_S = -5°C$,
$\omega = 0.75\%$



$q = 33.4\ kW/m^2$,
$T_S = -5°C$,
$\omega = 0.75\%$

Boiling pattern for T_s = -5 ºC, and ω = 0.75 % [14]

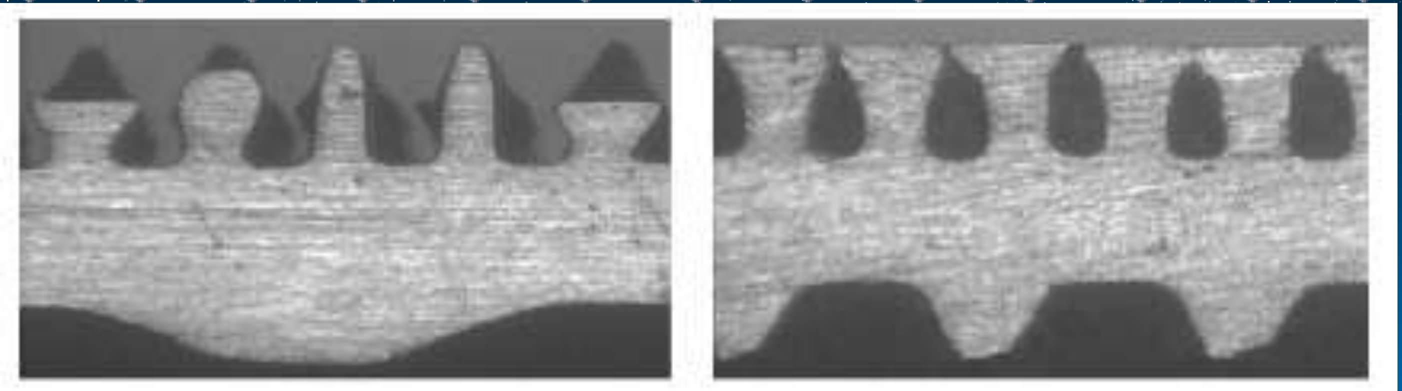
- For the same oil concentration
  - the depth of the foaming increases when the saturation temperature is decreased
- The size of the foaming
  - increased as the saturation temperature is decreased

- The effect of foaming are more evident in higher oil concentration and at a lower saturation temperature
- The results may explain the sharp bounce of heat transfer coefficient of Zheng et al.’s data [13]

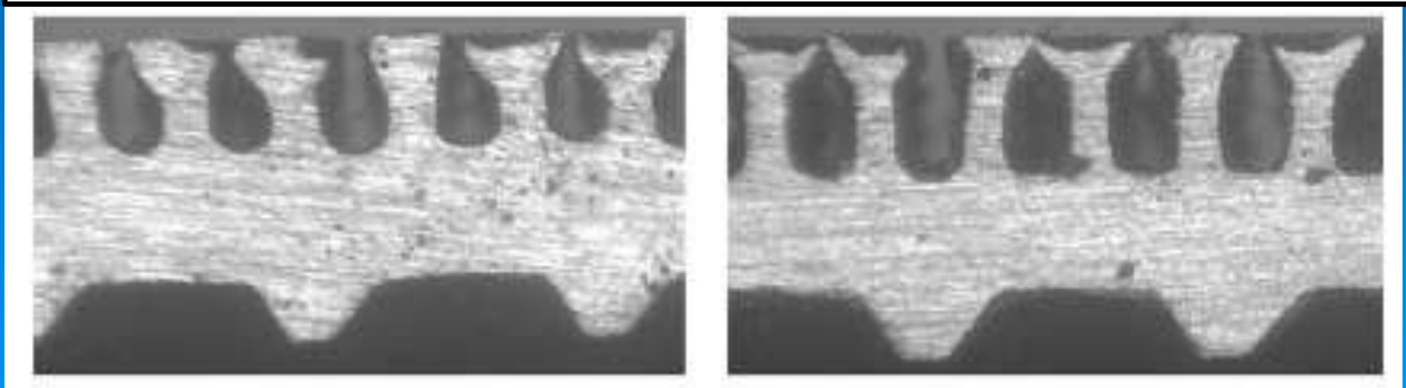
Effect of geometry

- For standard tube geometries (smooth and low finned tubes)
  - the heat transfer increases by adding oil to the refrigerant.
- For enhanced tubes
  - the oil plugs the micro channels of the surface structure for oil mass fractions greater than 5% and high heat fluxes.

Test results for Ji et al.

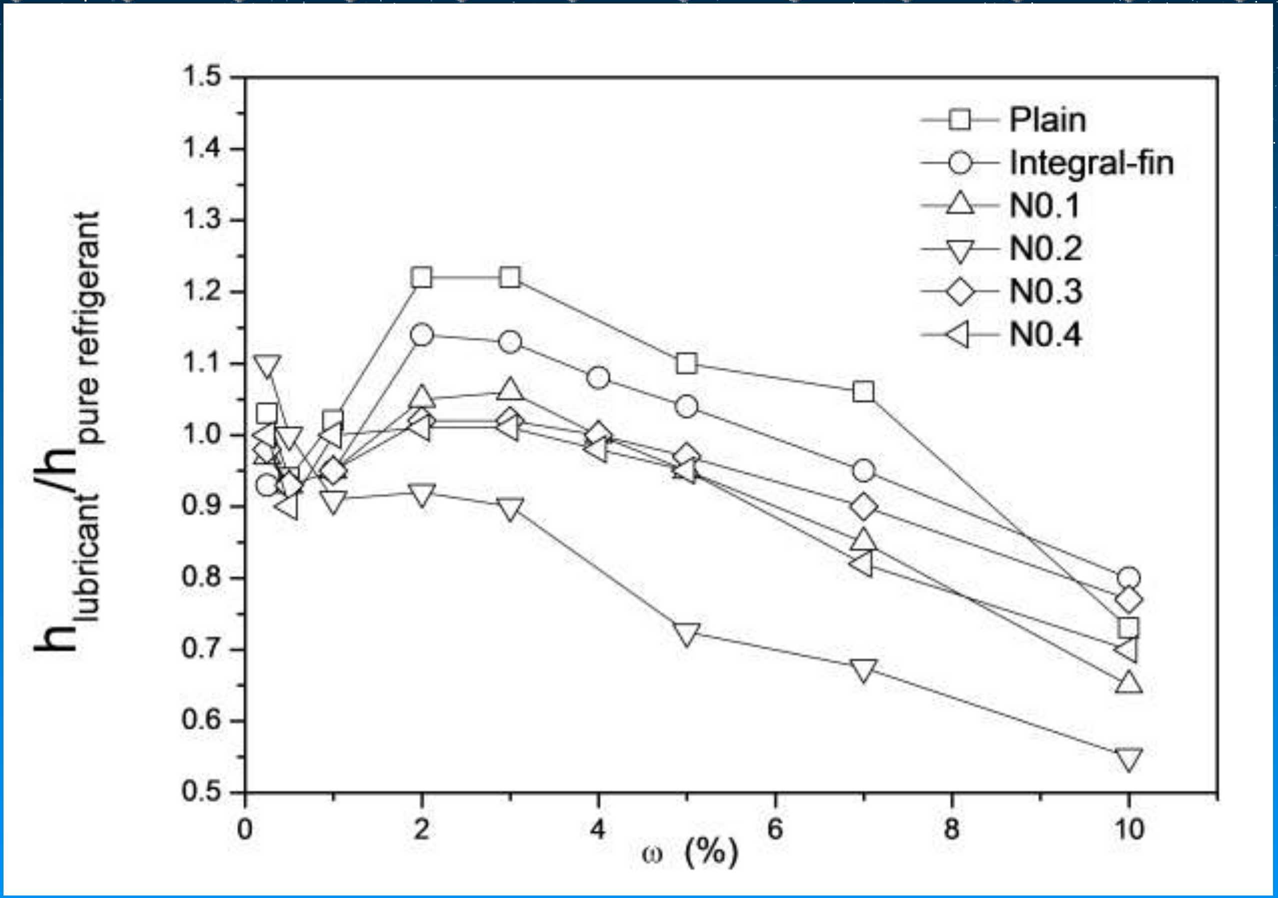


#1, 1435 fins/m #2, 1561 fins/m

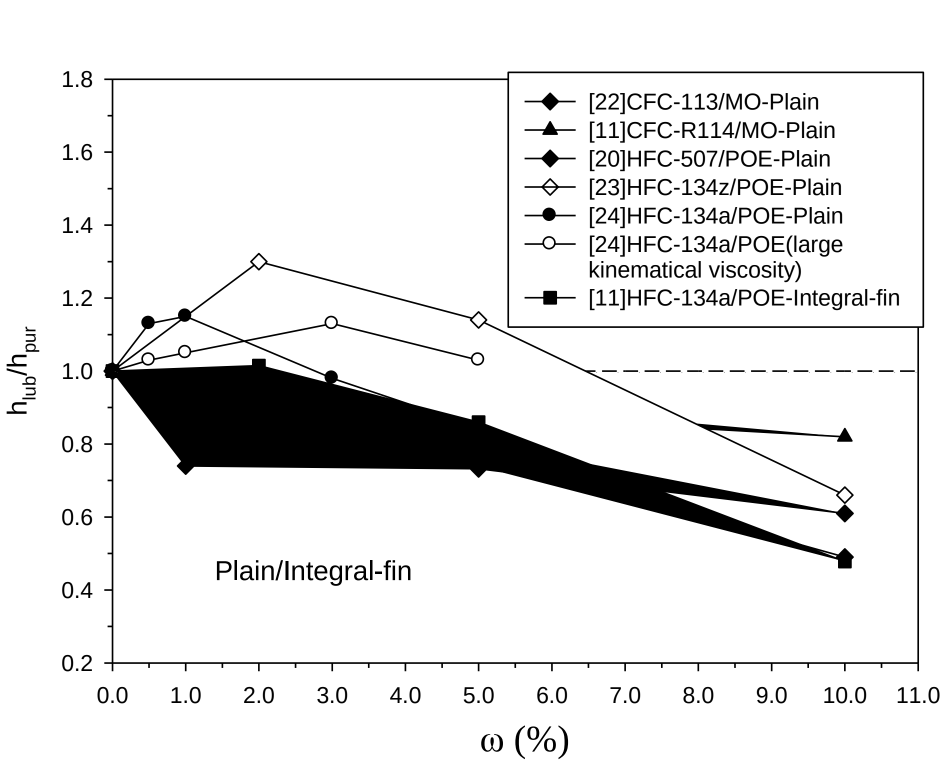


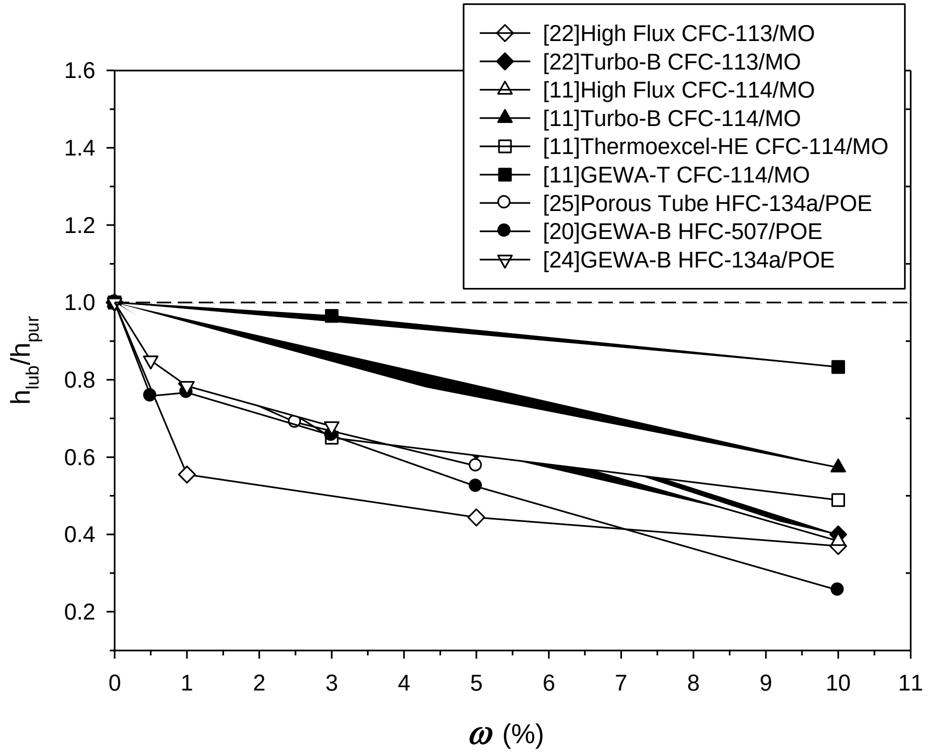
#3, 1696 fins/m #4, 1761 fins/m

Schematic of the enhanced tube structure by Ji et al. [21]



Variation of the relative boiling heat transfer coefficient of R-134a/lubricant.





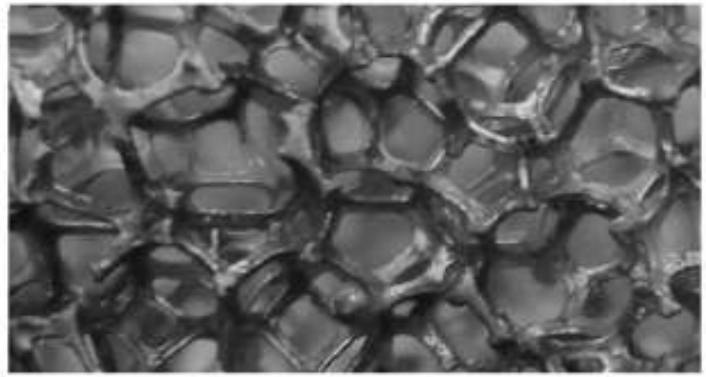
Plain/integral tube

Highly structured tube

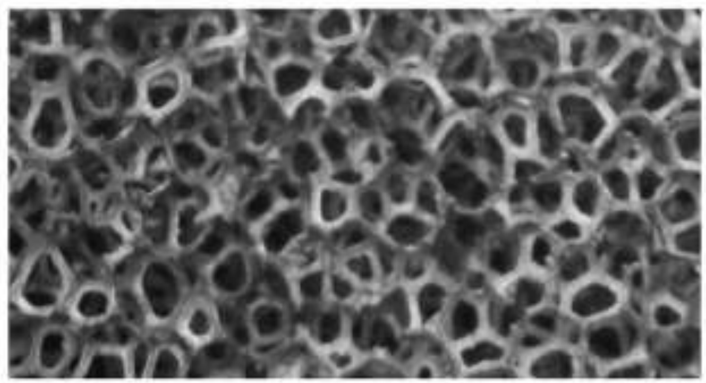
Variation in the relative boiling heat transfer coefficient of lubricant-mixed refrigerant reported in literatures

- performed nucleate boiling test on metal foam with porosity ranging from 90% to 98% as well as flat plate using R-113/VG68 shows an opposite trend.

Zhu et al. [26]



b Copper foam #2: ppi=10, Porosity=95%



c Copper foam #3: ppi=20, Porosity=98%

Photos of the metal foam tested by Zhu et al. [26]

Effect of miscibility

- In the whole range of temperature, pressure and concentration
  - the refrigerant/lubricant mixtures may not be fully miscible
- In a mixture of refrigerant and lubricating oil
  - the liquid is separated almost in an oil enriched and a refrigerant enriched liquid phase

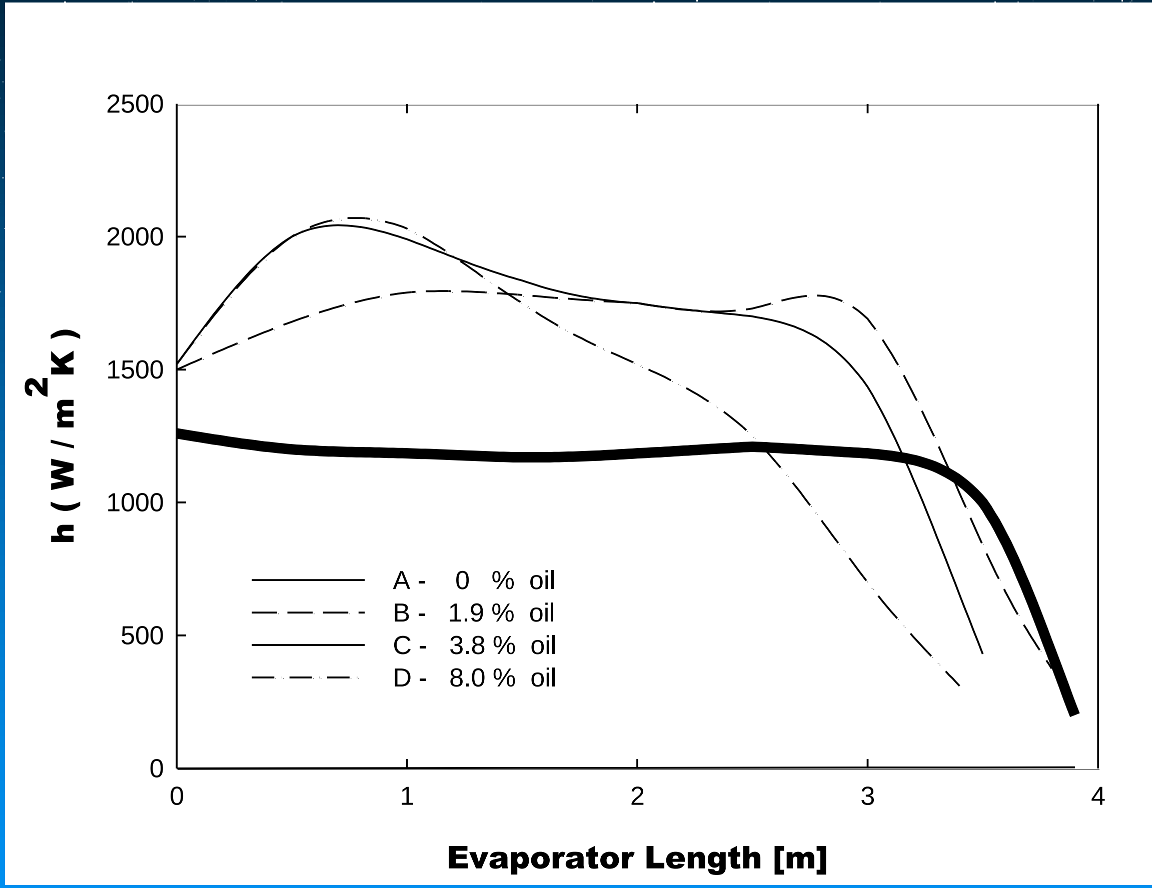
- The effective oil mass fraction increases around the heating surface since the refrigerant is more volatile.
- In the range of immiscibility
  - the ratio of enhancement is less than 1.0 caused by the oil which plugs the nucleation sites and the degradation becomes more pronounced for enhanced tube.

Effect of Lubricant on Convective Boiling

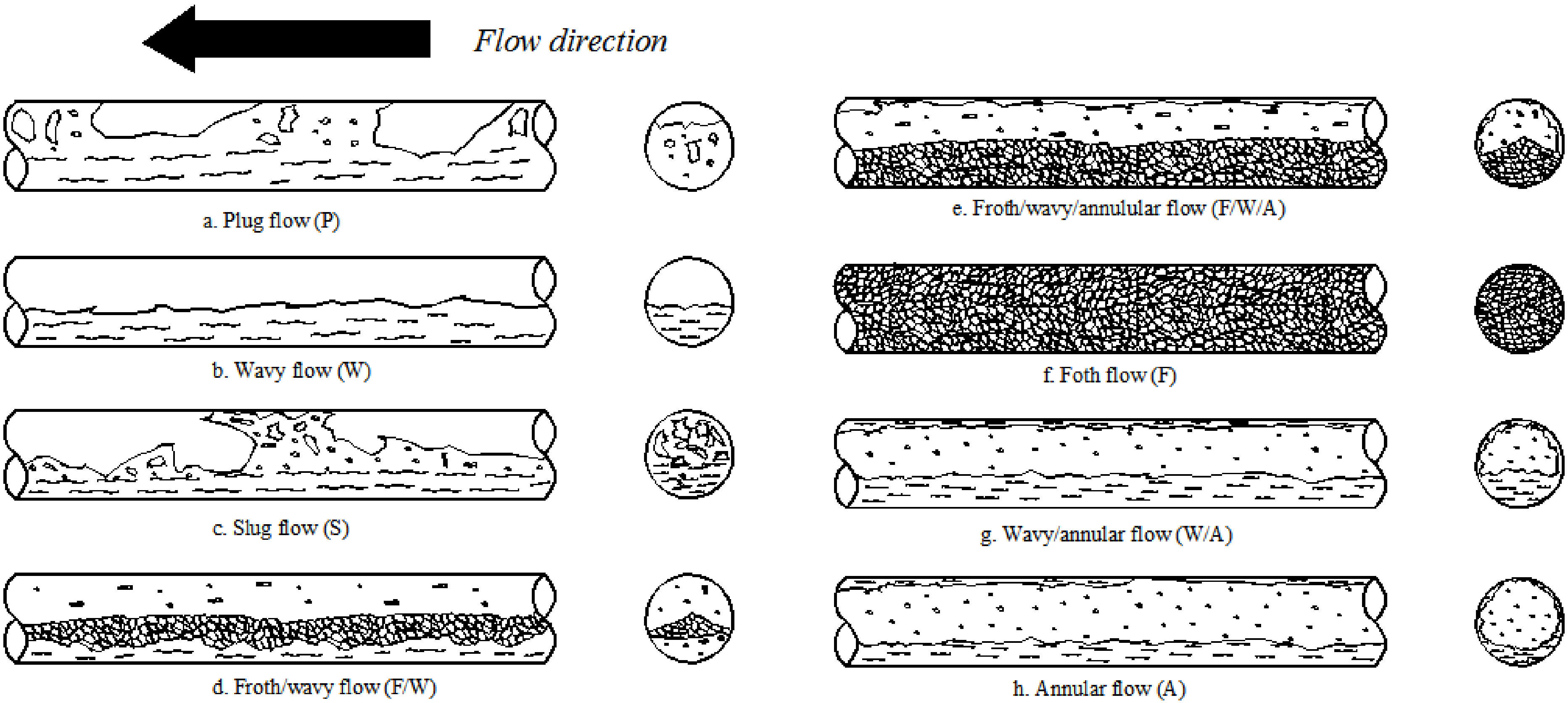
- The presence of lubricant increases the viscosity which normally lessen the degree of mixing of refrigerant mixtures
- leading to a decline of heat transfer performance

Oil concentration effect

- The enhancement apparently depends on
  - lubricant oil
  - heat flux
  - flow rate
  - flow patterns
  - the type of tube and other parameters
- yet the exact enhancement mechanism was not clearly identified



Local HTC as a function of evaporator length at -15 °C (Worsöe-Schmidt [22])



Sketch of flow patterns subject to influence of lubricant [32]

- The above-mentioned results may imply an early transition from wavy to annular flow pattern at a lower value of UGS.
- According to Taitel and Dukler [35], the transition from stratified to intermittent or annular flow will occur when

$$U_{GS} > \left(1 - \frac{H_L}{D}\right) \left\{ \frac{(\rho_L - \rho_G) g A_G}{\rho_G \frac{dA_L}{dH_L}} \right\}^{1/2}$$

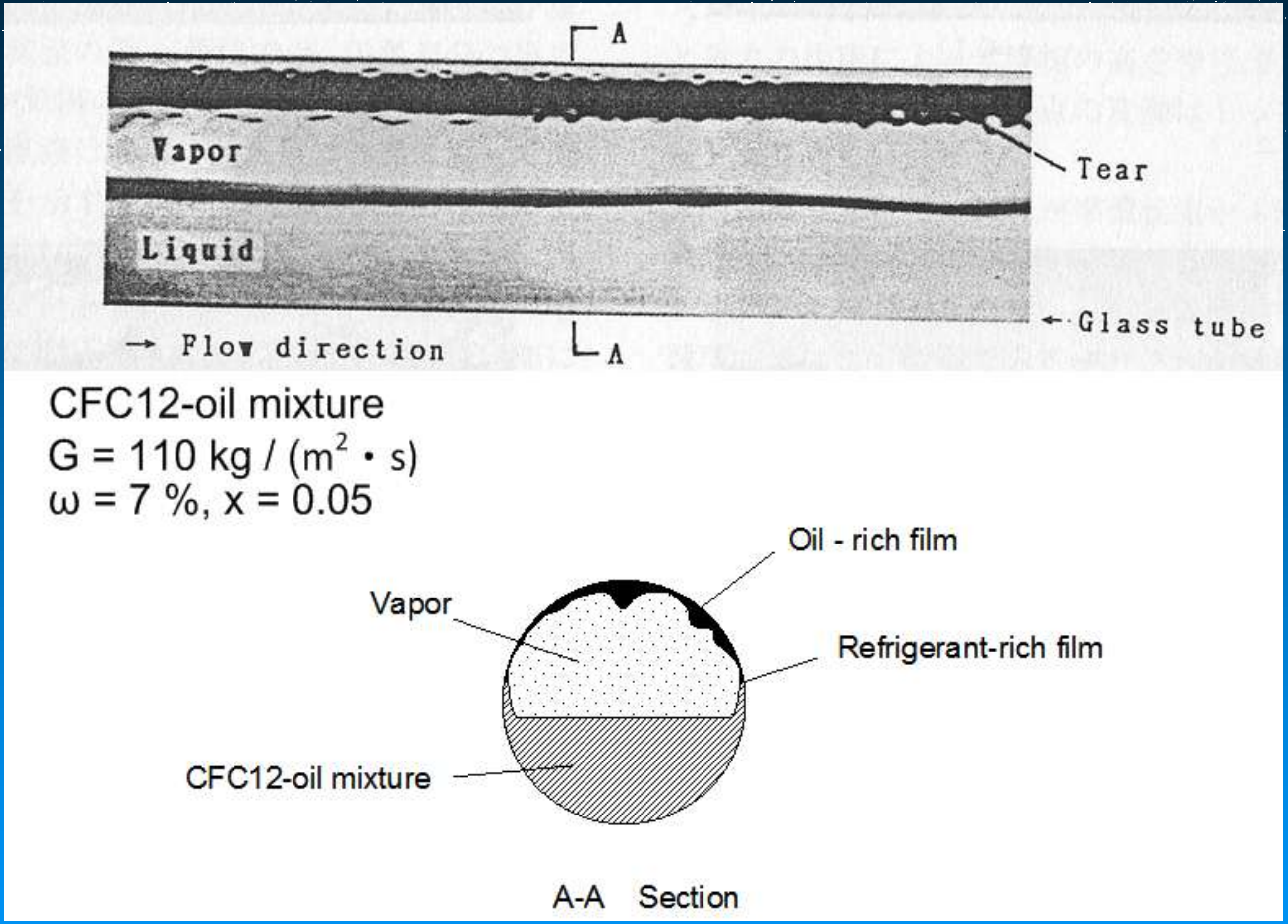
Hambraeus et al. [36]
Viscosity Effect

- Studied three ester-based lubricants mixed with R-134a.
  - the largest flow boiling degradation corresponded to the lubricant with the largest viscosity.

McMullan et al. [37]

- The flow boiling heat transfer of R-12 mixed with three lubricants
  - at an oil concentration of 1%
    - the overall evaporator performance degraded with an increase of the oil viscosity
  - At an oil concentration of 3%
    - the trend was reversed

Viscosity Effect



Schematic of the two-phase annular flow pattern of R-12/oil mixtures with oil-rich tear flow pattern at the upper part of the tube [33]

Mass velocity effect

- at low mass velocity (stratified/wavy flow)
  - the foaming formation happens on the liquid–vapor interface
- at high mass velocities (annular flow)
  - it is possible to observe froth flow like those observed by Wongwises et al. [32]

Vapor quality effect

- With the presence of tear like pattern, the oil-rich layer in the upper portion of the horizontal tube may impair the heat transfer performance considerably.
- Observed that in many experimental results the effect of lubricant oil concentration was not important at vapor qualities below about 85%.

Thome [38]

Effect of geometry of tube

- Since microfin tubes promote the annular flow pattern even at low mass velocities, the presence of lubricant oil in the refrigerant can lose its benefit to induce annular flow as observed in smooth tubes.

Effect of Lubricant on shell side condensation

- performed condensation tests for R-11 with 150 and 550 SSU at 37.8 °C
- no change in heat transfer coefficient when the concentration is less than 3%
- an appreciable decrease is encountered when the oil concentration is above 7%.

Williams and Sauer [42]

- investigated the condensation of R-11/oil mixtures on low finned tubes
  - using the same apparatus of [42]
- a negligible influence of lubricant oil on the condensation heat transfer coefficient

Sauer and Williams [43]

Wang et al. [44, 45]

- Conducted experimental study for R-12 and R-22 on the external surface of single and multiple horizontal plain tubes
  - the average decrease in the condensing heat transfer coefficient is 2% for every 2% increase of oil concentration (R-12) and 3% for R-22.

Adbul'Manov and Mirmov [46]

- Performed experiments for ammonia-oil mixtures
  - the presence of oil may result in partial dropwise condensation, and an enhancement of HTC

Effect of Lubricant on convective condensation

- Measured the heat transfer and pressure drop performance of R-134a/oil mixtures.
- For the refrigerant/oil mixture
  - a higher condensation coefficient at the beginning of the condenser
  - a lower heat transfer coefficient toward the latter part of the condenser.

Shao and Granryd [47]

Effect of Oil Concentration

- The HTC of refrigerant/oil mixtures is very close to each other and reveals slight decrease with the rise of oil concentration.

Schlager et al. [48] and Eckels et al. [49]

- developed a correlation to describe the influence of oil concentration:

$$\frac{h_{oil}}{h_{no-oil}} = e^{-2.2\omega}$$

Bassi and Bansal [50]

Effect of Tube Geometries

- the presence of oil reduces the condensation heat transfer in smooth tubes and micro-fin tubes at the same level
- the presence of oil is less important low-fin tubes for the low-fin tubes have a larger fin height than the micro-fin tubes

Schlager et al. [48]

- the addition of lubricant decreased the condensation pressure drop but the effect is not found in microfin tube.

Schlager et al. [48]

- conducted R-410A/oil mixture inside small diameter microfin tubes (4 mm)
  - a transition quality exists about the influence of lubricant on pressure drop.

Huang et al. [55]

The frictional pressure drop of R-410A/oil mixtures

- the vapor quality is lower than 0.6
  - decrease by a maximum of 18%
- the vapor quality exceed 0.6
  - increase by a maximum of 13%

- conducted condensation of R-134a subject to SUS169 & SUS369 lubricant
- the condensation pressure drop for SUS 369 is nearly identical to the oil-free tests
  - with ω up to 5%
- the condensation pressure drop for SUS 169 is much higher than the oil-free tests
  - 55% for ω = 5% and G = 200 kg/m^2s

Eckels et al. [49]

- When G is increased to 300 kg/m2s
  - the pressure drop penalty ratio (in terms of $\Delta p_{oil}/\Delta p_{oil\text{-}free}$) for SUS 169 lubricant is appreciably reduced
- With the rise of mass flux
  - the significant vapor shear may give rise to considerable lubricant entrainment

Effect of Mixture Viscosity

- The degradation of the condensation heat transfer coefficient
  - the higher viscosity of the refrigerant/oil liquid film as compared to the pure refrigerant
- The higher viscosity reduces the molecular and turbulent transport in the condensate film

Shao and Granryd [47]

Effect of Vapor Quality

- However, the conclusion seems not to be in line with some experimental results
  - Chitti and Anand [44] and Eckels et al. [49]
- The heat transfer coefficient of R-22/oil and R-407C/oil decreased with an increase in inlet quality
- A substantial rise of the second section after the return bend

Cho and Tae [56]

- The presence of oil at low concentrations
  - insignificant effect on the heat transfer coefficient in low quality region
  - a more pronounced deterioration is encountered at higher qualities
- At high oil concentrations of 10% or more
  - the oil presence affects the heat transfer coefficient uniformly over the entire quality range

Cawte [57]

- The pure refrigerant condensation coefficient
  - decreases toward lower vapor qualities
- Upon refrigerant/oil mixtures
  - a maximum in heat transfer coefficient occurred at certain vapor quality

Fukushima and Kudou [58]

- At high vapor qualities
  - the liquid film is thin but oil-rich, which results in a higher mass transfer resistance effect and higher viscosity in the film
- As the vapor quality decreases
  - the liquid film becomes thicker
  - more dissolved refrigerant decreases the effects of the lubricant in the film

Short Summary

- The lubricant effect on HTC is quite complex
  - especially for pool and convective boiling
- The lubricant can, increase or impair the heat transfer performance depending on
  - oil concentration, surface tension, surface geometry, and the like.

- For the condensation
  - it is more well accepted that the presence of lubricant normally will impair the heat transfer performance due to deposited oil film
- However, the deterioration is comparatively smaller than that in nucleate/convective boiling.

Acknowledgments

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Thanks For Your Attention