

# 10. GAIA

## IRAKITEA ETA KONDENTSAZIOA

### 10.0 - HELBURUAK

2/28

- **Lurrunketa** eta **irakitea** desberdindu, eta zenbait irakite modu bereizi,
- **Irakite-kurba** eta irakite-kurbaren eskualdeetako irakite-erregimenak ondo ulertu
- **Bero-fluxua** kalkulatu eta, orobat, **irakite nukleatuari** lotutako balio kritikoa, eta irakiteprozesuko bero-transferentzia indartzeko metodoak aztertu
- Xafla bertikalen gaineko **geruza-erako kondentsazio laminarreko** bero-transferentziaren koefizientearen erlazioa garatu
- Xafla inklinatuetan eta horizontaletan, zilindro bertikaletan eta horizontaletan, esferetan eta hodi multzoetan gertatzen den **kondentsazioko bero-fluxua** kalkulatu
- **Tanta-erako kondentsazioa** aztertu eta haren ziurgabetasun batzuk ulertu.

**Lurrunketa**

Likido-lurrin faseartea

Lurrin-presioa  $< P_{sat}(T_{jariakin})$ **Irakitea**

Solido-likido faseartea

Gainazalarekin kontaktuan dagoen likidoa  $T_s > T_{sat}$ 

Lurrin-burbuilak azkar sortzen dira, zeinak gainazaletik askatzen baitira neurri jakin bat hartzen dutenean eta likidoaren gainazal askera igotzen saiatzen baitira

$$\dot{q}_{boiling} = h \cdot (T_s - T_{sat}) = h \cdot \Delta T_{excess} \quad [\text{W/m}^2]$$

## 10.1 – IRAKITE-PROZESUKO BERO-TRANSFERENTZIA

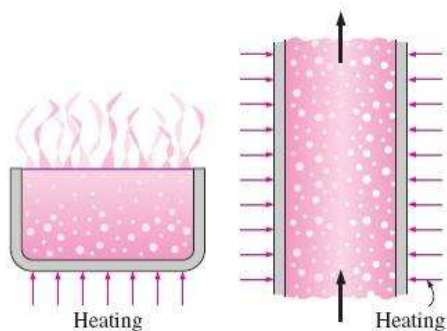
**Konbekzio behartu eta naturala** (fase bakarra) Propietateak:  $\mu$ ,  $\rho$ ,  $k$  eta  $c_p$

**Irakitea** Propietateak:  $\mu$ ,  $\rho$ ,  $k$  eta  $c_p$  (likido eta lurrinarena).

$h_{fg}$  = Lurruntze-bero sorra.

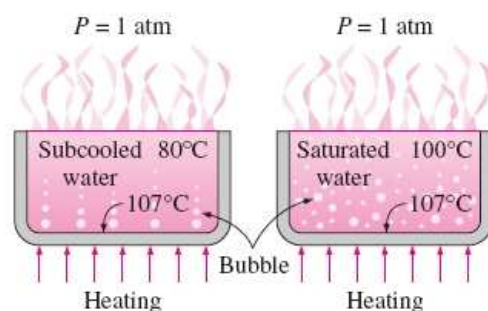
$\sigma$  = Gainazal-tentsioa.

Oreka-termodinamiko eza:  $P_v \neq P_l$        $T_v \neq T_l$



Tanga-erako  
irakitea

Fluxu-erako irakitea  
(irakitea konbekzio  
behartuan)

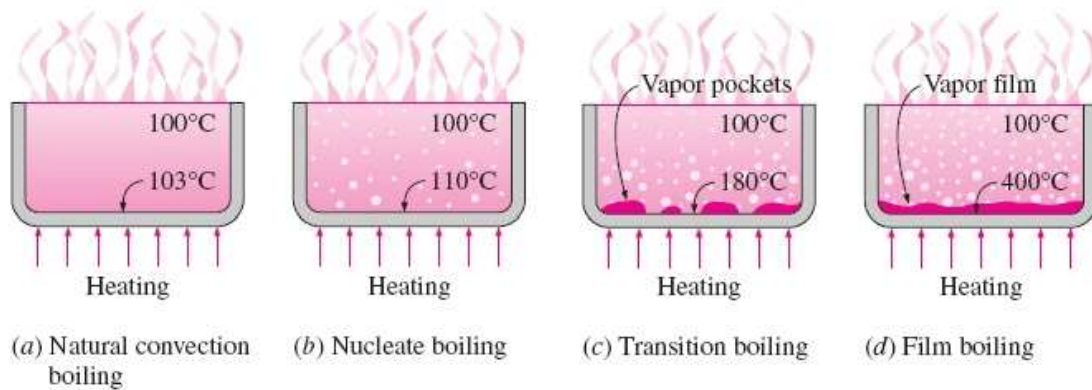


Irakite  
azpihoztua  
(lokala)

Irakite ase  
(globala)

## IRAKITE-ERREGIMENAK ETA IRAKITE-KURBA

Irakite prozesuak  $\Delta T_{\text{excess}}$ -ren arabera forma desberdinak har ditzake



Konbekzio natural  
bidezkoa irakitea

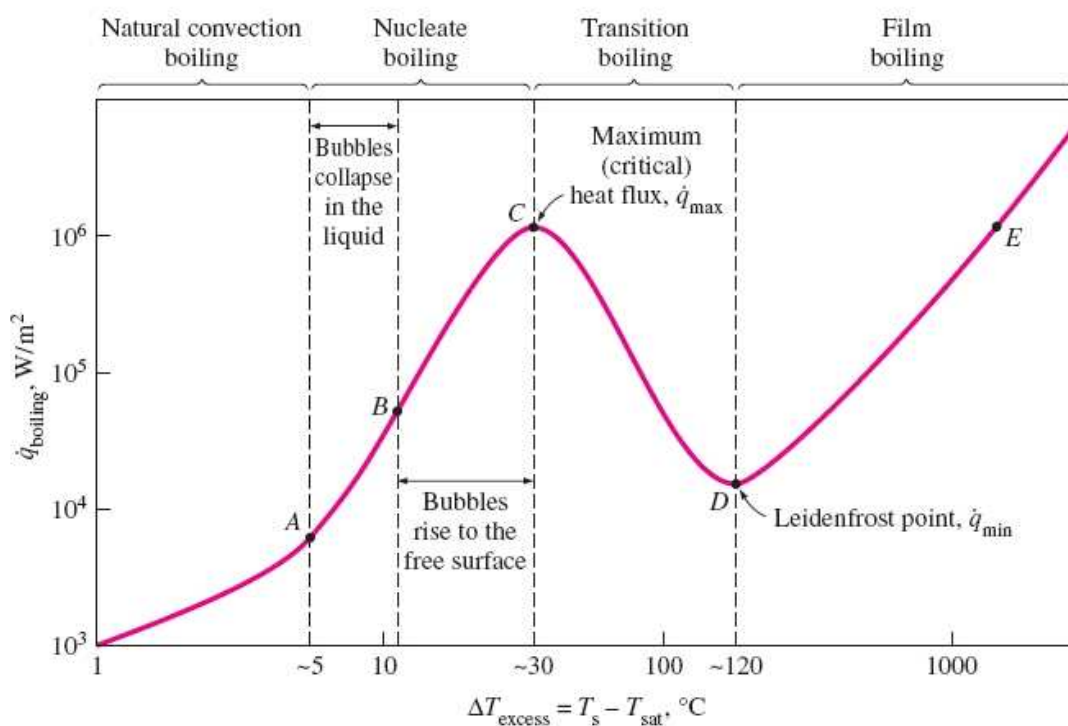
Irakite nukleatua

Trantsizio irakitea

Geruza erako irakitea

## 10.2 – TANGA-ERA KO IRAKITEA

## IRAKITE-ERREGIMENAK ETA IRAKITE-KURBA



## IRAKITE-ERREGIMENAK ETA IRAKITE-KURBA

## Konbekzio naturaleko irakitea (A puntura arte)

Likidoaren gainberoketa txikia (2-6 °C).

Konbekzio naturala

## Irakite nukleatua (A eta C puntuen artean)

Lehen burbuilak sortzen dira.

2 eskualde desberdin:

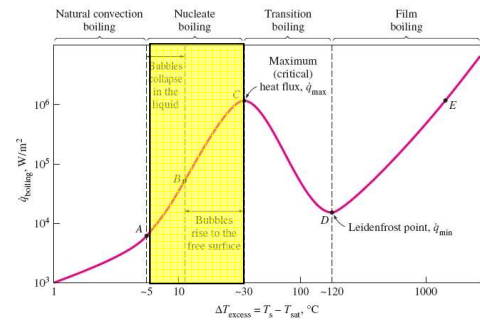
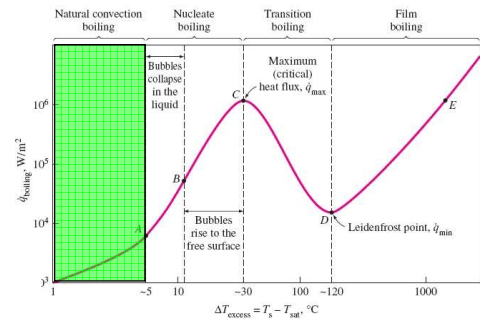
A-B: Burbuila isolatuak.

Likidoaren mugimendua

B-C: Lurrun-zutabe jarraituak sortzen dira.

Likidoaren mugitzea + lurrunketa efektuak

C: Bero-fluxu kritikoa  $\dot{q}_{\max}$



## IRAKITE-ERREGIMENAK ETA IRAKITE-KURBA

## Trantsizio-irakitea (C eta D puntuen artean)

Lurrun-geruza batek gainazalaren parte bat estaltzen du.

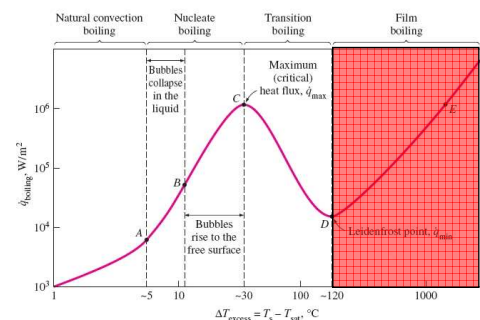
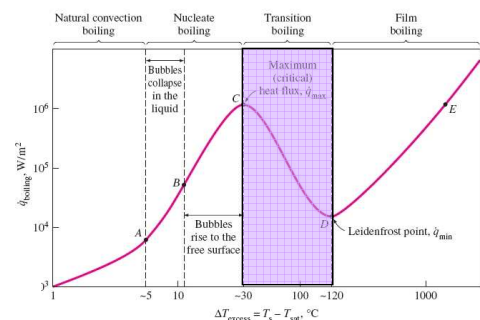
Irakite nukleatutik → Geruza-erako irakitera.

## Geruza-erako irakitea (D puntutik aurrera)

Lurrun geruza jarraitu eta egonkorra.

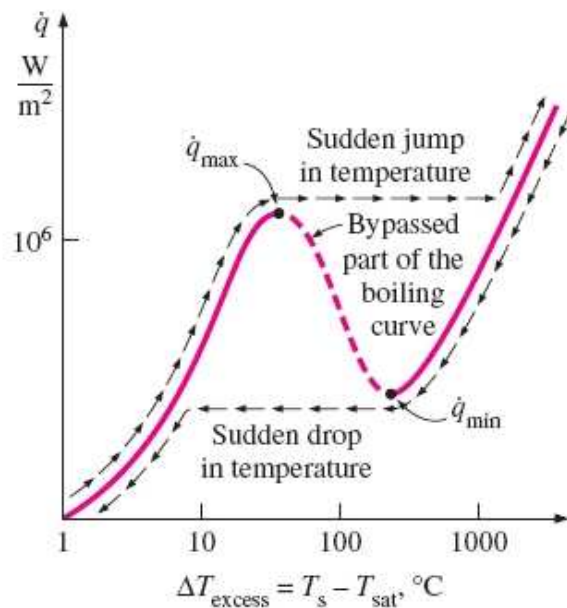
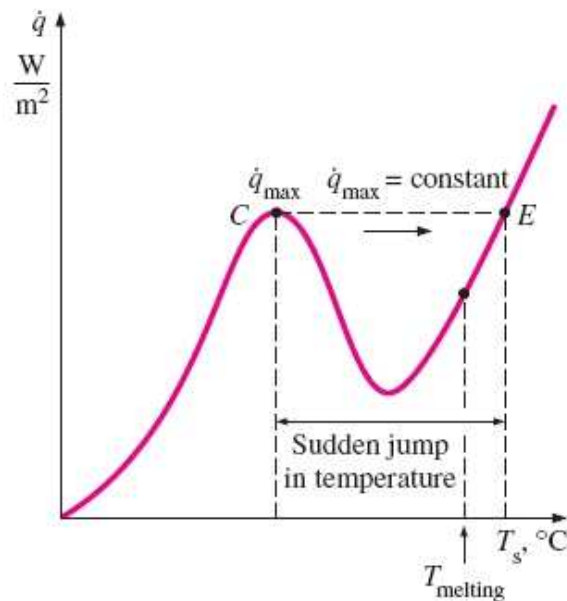
D: Leidenfrost puntua  $\dot{q}_{\min}$

Lurrun-geruzan erradiazio bero-transferentzia.



## IRAKITE-ERREGIMENAK ETA IRAKITE-KURBA

## Irakite-kurba erreala



## 10.2 – TANGA-ERA KO IRAKITEA

TANGA-ERA KO  
KORRELAZIOAK

## IRAKITE-PROZESUKO

## BERO-TRANSFERENTZIAKO

Konbekzio naturaleko irakitea → 9. GAIA

## Irakite nukelatua

**Rohsenow**  
(propietateak  $T_{sat}$ )

$$\dot{q}_{nucleate} = \mu_l \cdot h_{fg} \cdot \left[ \frac{g \cdot (\rho_l - \rho_v)}{\sigma} \right]^{1/2} \left[ \frac{C_p \cdot (T_s - T_{sat})}{C_{sf} \cdot h_{fg} \cdot Pr_l^n} \right]^3$$

## Errorea:

$$\pm 100 \% q-n$$

$$\pm 30 \% \Delta t_{excess}-n$$

 $\dot{q}_{nucleate}$  = nucleate boiling heat flux, W/m<sup>2</sup> $\mu_l$  = viscosity of the liquid, kg/m · s $h_{fg}$  = enthalpy of vaporization, J/kg $g$  = gravitational acceleration, m/s<sup>2</sup> $\rho_l$  = density of the liquid, kg/m<sup>3</sup> $\rho_v$  = density of the vapor, kg/m<sup>3</sup> $\sigma$  = surface tension of liquid–vapor interface, N/m $C_{pl}$  = specific heat of the liquid, J/kg · °C $T_s$  = surface temperature of the heater, °C $T_{sat}$  = saturation temperature of the fluid, °C $C_{sf}$  = experimental constant that depends on surface–fluid combination $Pr_l$  = Prandtl number of the liquid $n$  = experimental constant that depends on the fluid



TANGA-ERA KO  
KORRELAZIOAKSurface tension of liquid–vapor  
interface for water

$T, ^\circ\text{C}$	$\sigma, \text{N/m}^*$
0	0.0757
20	0.0727
40	0.0696
60	0.0662
80	0.0627
100	0.0589
120	0.0550
140	0.0509
160	0.0466
180	0.0422
200	0.0377
220	0.0331
240	0.0284
260	0.0237
280	0.0190
300	0.0144
320	0.0099
340	0.0056
360	0.0019
374	0.0

## IRAKITE-PROZESUKO

## BERO-TRANSFERENTZIAKO

Substance and Temp. Range	Surface Tension, $\sigma, \text{N/m}^* (T \text{ in } ^\circ\text{C})$
Ammonia, $-75$ to $-40^\circ\text{C}$ :	$0.0264 + 0.000223T$
Benzene, $10$ to $80^\circ\text{C}$ :	$0.0315 - 0.000129T$
Butane, $-70$ to $-20^\circ\text{C}$ :	$0.0149 - 0.000121T$
Carbon dioxide, $-30$ to $-20^\circ\text{C}$ :	$0.0043 - 0.000160T$

Values of the coefficient  $C_{sf}$  and  $n$  for various fluid–surface combinations

Fluid-Heating Surface Combination	$C_{sf}$	$n$
Water–copper (polished)	0.0130	1.0
Water–copper (scored)	0.0068	1.0
Water–stainless steel (mechanically polished)	0.0130	1.0
Water–stainless steel (ground and polished)	0.0060	1.0
Water–stainless steel (teflon pitted)	0.0058	1.0
Water–stainless steel (chemically etched)	0.0130	1.0
Water–brass	0.0060	1.0
Water–nickel	0.0060	1.0
Water–platinum	0.0130	1.0
$n$ -Pentane–copper (polished)	0.0154	1.7

TANGA-ERA KO  
KORRELAZIOAK

## IRAKITE-PROZESUKO

## BERO-TRANSFERENTZIAKO

Puntako bero-fluxua (  $\dot{q}_{\max}$  )Kutateladze y  
Zuber

$$\dot{q}_{\max} = C_{cr} \cdot h_{fg} \cdot [\sigma \cdot g \cdot \rho_v^2 (\rho_l - \rho_v)]^{1/4}$$

Values of the coefficient  $C_{cr}$  for use in Eq. 10–3 for maximum heat flux  
(dimensionless parameter  $L^* = L[g(\rho_l - \rho_v)/\sigma]^{1/2}$ )

Heater Geometry	$C_{cr}$	Charac. Dimension of Heater, $L$	Range of $L^*$
Large horizontal flat heater	0.149	Width or diameter	$L^* > 27$
Small horizontal flat heater <sup>1</sup>	$18.9K_1$	Width or diameter	$9 < L^* < 20$
Large horizontal cylinder	0.12	Radius	$L^* > 1.2$
Small horizontal cylinder	$0.12L^{*-0.25}$	Radius	$0.15 < L^* < 1.2$
Large sphere	0.11	Radius	$L^* > 4.26$
Small sphere	$0.227L^{*-0.5}$	Radius	$0.15 < L^* < 4.26$

$$^1K_1 = \sigma/[g(\rho_l - \rho_v)A_{\text{heater}}]$$

TANGA-ERA KO  
KORRELAZIOAK

## IRAKITE-PROZESUKO

## BERO-TRANSFERENTZIAKO

Bero-fluxu minimoa (  $\dot{q}_{\min}$  )Zuber  
(xafla handi  
horizontala)

$$\dot{q}_{\min} = 0,09 \cdot \rho_v \cdot h_{fg} \cdot \left[ \frac{\sigma \cdot g \cdot (\rho_l - \rho_v)}{(\rho_l + \rho_v)^2} \right]^{\frac{1}{4}}$$

Errorea ~ 50 % edo handiagoa

Geruza-erako irakitea

Bromley  
(zilindro horizontala  
edo esfera)

$$\dot{q}_{film} = C_{film} \left[ \frac{g k_v^3 \rho_v (\rho_l - \rho_v) [h_{fg} + 0,4 \cdot C_{pv} (T_s - T_{sat})]}{\mu_v D (T_s - T_{sat})} \right]^{\frac{1}{4}}$$

$$C_{film} = \begin{cases} 0,62 \text{ zilindro horizontaletan} \\ 0,67 \text{ esferetan} \end{cases}$$

$$\text{Propietateak} \begin{cases} \text{Lurrun-geruzaren tenperaturan } T_f = \frac{T_s + T_{sat}}{2} \\ \text{Likidoa eta } h_{fg} \text{ asetatsun tenperaturan.} \end{cases}$$

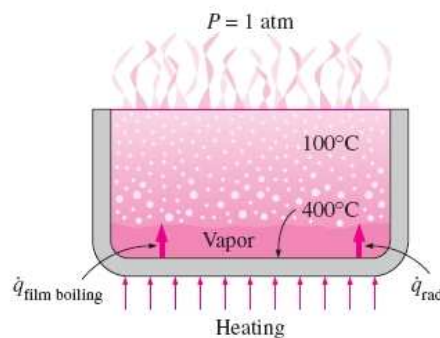
## 10.2 – TANGA-ERA KO IRAKITEA

TANGA-ERA KO  
KORRELAZIOAK

## IRAKITE-PROZESUKO

## BERO-TRANSFERENTZIAKO

Geruza-erako irakitea

•  $T_s \uparrow \rightarrow$  Erradiazioa

$$\dot{q}_{rad} = \varepsilon \cdot \sigma \cdot (T_s^4 - T_{sat}^4)$$

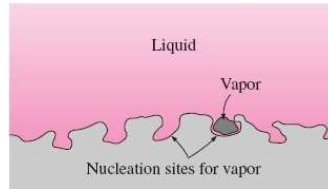
Baldin  $\dot{q}_{rad} < \dot{q}_{film}$ 

Bromley

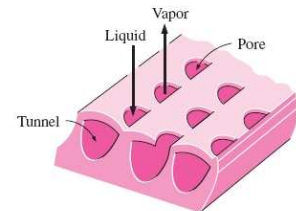
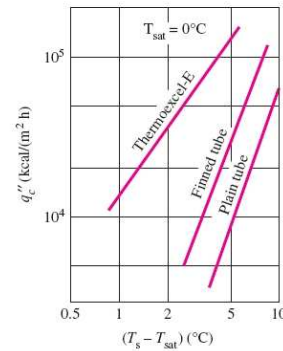
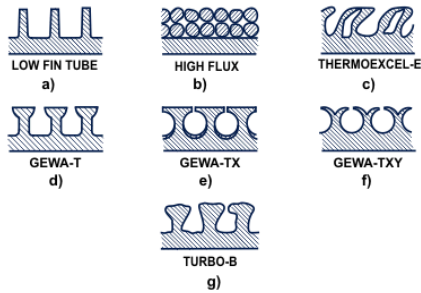
$$\dot{q}_{total} = \dot{q}_{film} + \frac{3}{4} \dot{q}_{rad}$$

## TANGA-ERA KO IRAKITE-PROZESUKO BERO-TRANSFERENTZIA INDARTZEA

Zimurtasuna eta hautsa  
(gainazal irregulartasunak)



Bero-transferentzia hobetzen duten  
gainazalak



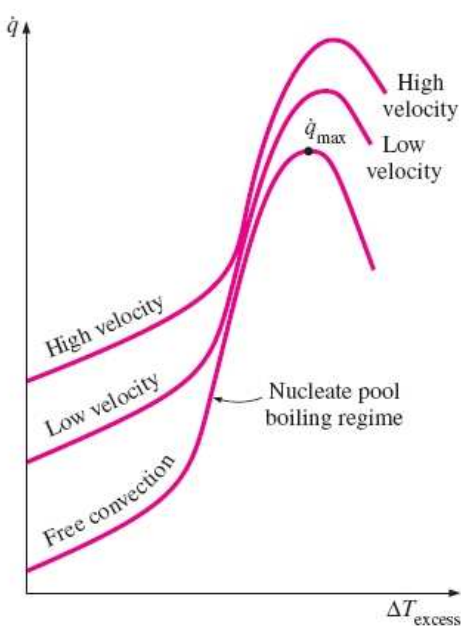
Mekanikoki eraginda

Gainazal-bibrazioa

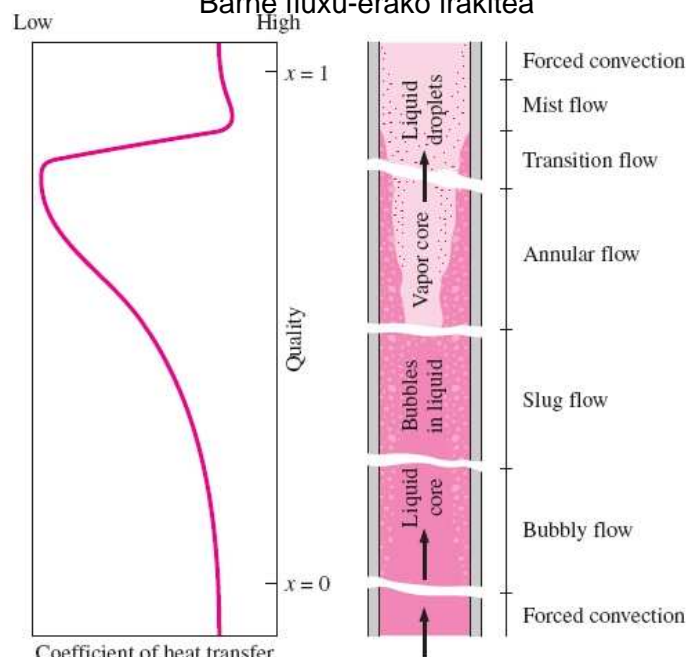
## 10.3 – FLUXU-ERA KO IRAKITEA

Konbekzio eta tanga-erako irakitearen efektu bateratuak

Kanpo fluxu-erako irakitea



Barne fluxu-erako irakitea

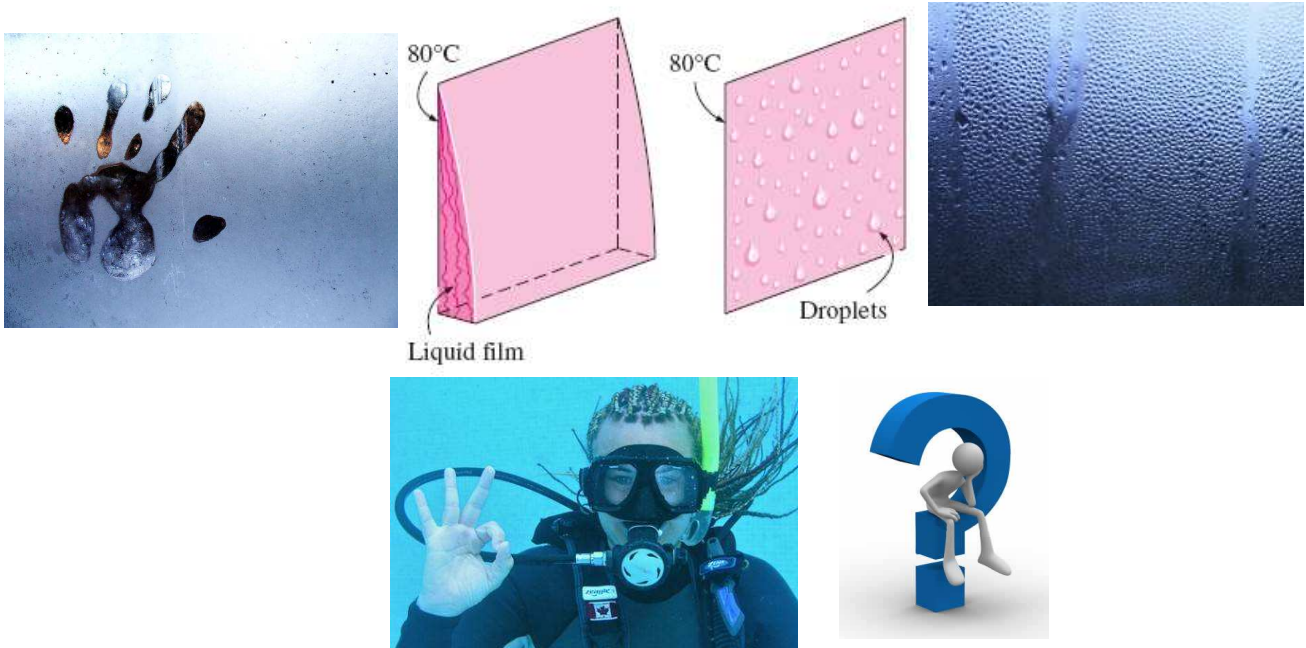


Estimazio gordina:

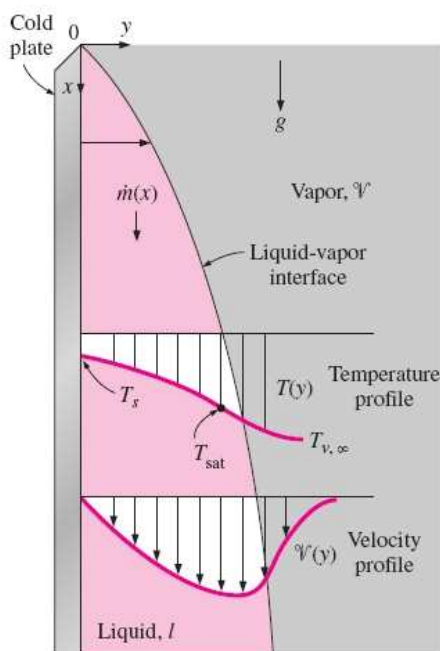
$$\dot{q}_{\text{flow boiling}} = \dot{q}_{\text{forced convection}} + \dot{q}_{\text{pool boiling}}$$



- Lurrun baten tenperatura haren  $T_{\text{sat}}$ -tik behera jaistean.
- Gainazal solidoen gaineko kondentsazioa.
- Bi motakoak: **Geruza-erako kondentsazioa** **Tanta-erako kondentsazioa**



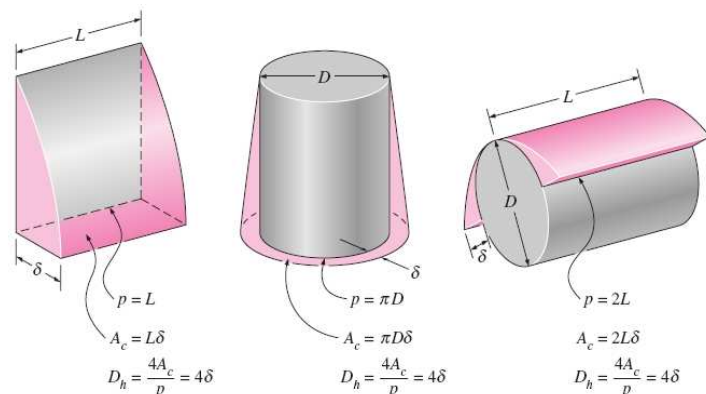
# 10.5 – GERUZA-ERAKO KONDENTSazioA



	T	V
Solido – likido faseartea	$T_s$	0
Likido – lurrun faseartea	$T_{\text{sat}}$	$V_{\text{max}}$

$$Re = \frac{D_h \rho_l V_l}{\mu_l} = \frac{4 \cdot \dot{m}}{p \mu_l}$$

$\dot{m}$  = Beheko aldeko kondentsatuaren masa emaria [kg/s]



Kondentsatuak  $T_s$  eta  $T_{sat}$  tarteko tenperatura batera azpihozten da.

**Rohsenow**  
(Lurrunketa bero sorra  
eraldatua)

$$h_{fg}^* = h_{fg} + 0.68 c_{pl} (T_{sat} - T_s)$$

$T_v$  tenperatura bateko lurrun gainberotuan:

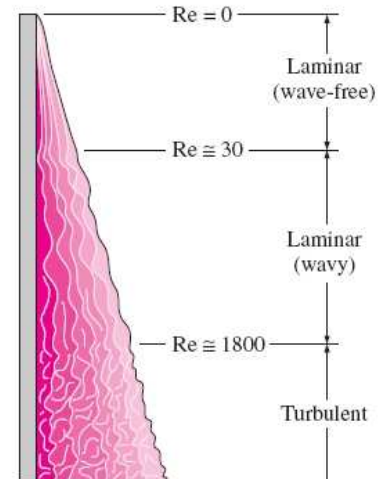
$$h_{fg}^* = h_{fg} + 0.68 c_{pl} (T_{sat} - T_s) + c_{pv} (T_v - T_{sat})$$

$$\dot{Q}_{condens} = h \cdot A_s \cdot (T_{sat} - T_s) = \dot{m} \cdot h_{fg}^*$$

$$Re = \frac{4 \cdot \dot{Q}_{condens}}{p \cdot \mu_l \cdot h_{fg}^*} = \frac{4 \cdot h \cdot A_s \cdot (T_{sat} - T_s)}{p \cdot \mu_l \cdot h_{fg}^*}$$

Likidoaren propietateak:  $T_f = \frac{T_{sat} + T_s}{2}$

$$h_{fg} = h_{fg}(T_{sat})$$



## 10.5 – GERUZA-ERA KO KONDENTSATZIOA

### GERUZA-ERA KO KONDENTSATZIOKO BERO-TRANSFERENTZIAREN KORRELAZIOAK

#### 1 – Xafla bertikalak – Fluxu laminarra

$T_s$  eta  $T_{sat}$  Konstanteak. Kondentsatuan aldaketa lineala.

Bero-transferentzia eroapen bidezkoa.

Lurrunaren abiadura txikia (arrasterik gabe)

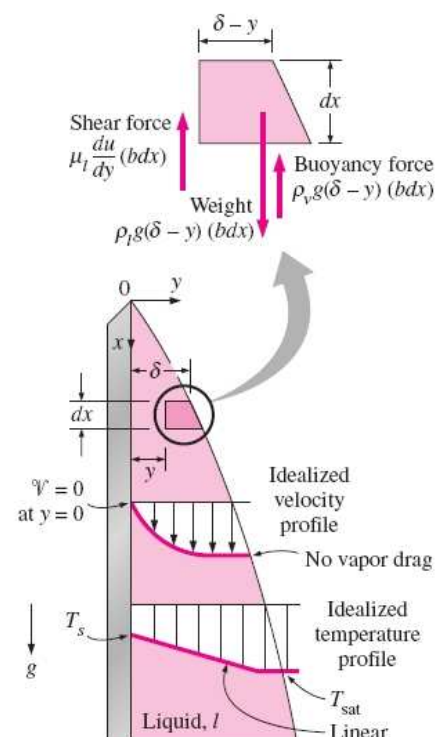
Kondentsatu-fluxu laminarra eta propietateak konstanteak.

Kondentsatu-geruzaren azelerazio baztergarria.

$$\sum F_x = m \cdot a_x = 0$$

$$\frac{du}{dy} = \frac{g(\rho_l - \rho_v)(\delta - y)}{\mu_l} \Rightarrow$$

$$u = \frac{g(\rho_l - \rho_v)}{\mu_l} \left( y\delta - \frac{y^2}{2} \right)$$



### GERUZA-ERA KO KONDENTSATZIOKO BERO-TRANSFERENTZIAREN KORRELAZIOAK

#### 1 – Xafla bertikalak – Fluxu laminarra

$$\dot{m}(x) = \int_A \rho_l u(y) dA = \int_0^\delta \rho_l u(y) b dy \Rightarrow \dot{m}(x) = \frac{g b \rho_l (\rho_l - \rho_v)}{3 \mu_l} \delta^3$$

$$d\dot{Q} = h_{fg} \cdot d\dot{m} = k_l \cdot (b dx) \frac{T_{sat} - T_s}{\delta} \Rightarrow \delta(x) = \left[ \frac{4 \mu_l k_l (T_{sat} - T_s)}{g \rho_l (\rho_l - \rho_v) h_{fg}} x \right]^{1/4}$$

$$\dot{q}_x = h_x \cdot (T_{sat} - T_s) = k_l \frac{T_{sat} - T_s}{\delta} \Rightarrow h_x = \frac{k_l}{\delta(x)}$$

$$h_x = \left[ \frac{g \rho_l (\rho_l - \rho_v) h_{fg} k_l^3}{4 \mu_l (T_{sat} - T_s) x} \right]^{1/4}$$

$$h_{vert} = \frac{1}{L} \int_0^L h_x dx = \frac{4}{3} h_{x=L} \Rightarrow h = 0.943 \left[ \frac{g \rho_l (\rho_l - \rho_v) h_{fg} k_l^3}{\mu_l (T_{sat} - T_s) L} \right]^{1/4}$$

### 10.5 – GERUZA-ERA KO KONDENTSATZIOA

### GERUZA-ERA KO KONDENTSATZIOKO BERO-TRANSFERENTZIAREN KORRELAZIOAK

#### 1 – Xafla bertikalak – Fluxu laminarra

$$h_{vert} = 0.943 \left[ \frac{g \rho_l (\rho_l - \rho_v) h_{fg}^* k_l^3}{\mu_l (T_{sat} - T_s) L} \right]^{1/4} \quad [\text{W/m}^2 \cdot ^\circ\text{C}] \quad 0 < \text{Re} < 30$$

Hurrengo ekuazioak kontutan hartuz eta  $\rho_v \ll \rho_l$  suposatuz

$$\left\{ \begin{array}{l} \text{Re} = \frac{4 \cdot \dot{m}}{p \mu_l} \quad \dot{m}(x) = \frac{g b \rho_l (\rho_l - \rho_v)}{3 \mu_l} \delta^3 \\ h_x = \frac{k_l}{\delta(x)} \quad h_{vert} = \frac{4}{3} h_{x=L} \end{array} \right.$$

$$\text{Re} \cong \frac{4 g \rho_l (\rho_l - \rho_v) \delta^3}{3 \mu_l^2} = \frac{4 g \rho_l^2}{3 \mu_l^2} \left( \frac{k_l}{h_{x=L}} \right)^3 = \frac{4 g}{3 v_l^2} \left( \frac{k_l}{3 h_{vert} / 4} \right)^3$$

$$h_{vert} \cong 1.47 k_l \text{Re}^{-1/3} \left( \frac{g}{v_l^2} \right)^{1/3} \quad 0 < \text{Re} < 30 \quad \rho_v \ll \rho_l$$

## GERUZA-ERA KO KONDENTSATZIOKO BERO-TRANSFERENTZIAREN KORRELAZIOAK

### 1 – Xafla bertikalak – Fluxu laminar izurtua

Kutateladze

$$h_{vert, wavy} = \frac{k_l Re}{1.08 Re^{1.22} - 5.2} \left( \frac{g}{v_l^2} \right)^{1/3} \quad 30 < Re < 1800 \quad \rho_v \ll \rho_l$$

$$h_{vert, wavy} = 0.8 Re^{0.11} h_{vert}$$

$$Re_{vert, wavy} = \left[ 4.81 + \frac{3.70 L k_l (T_{sat} - T_s)}{\mu_l h_{fg}^*} \left( \frac{g}{v_l^2} \right)^{1/3} \right]^{0.820} \quad \rho_v \ll \rho_l$$

## 10.5 – GERUZA-ERA KO KONDENTSATZIOA

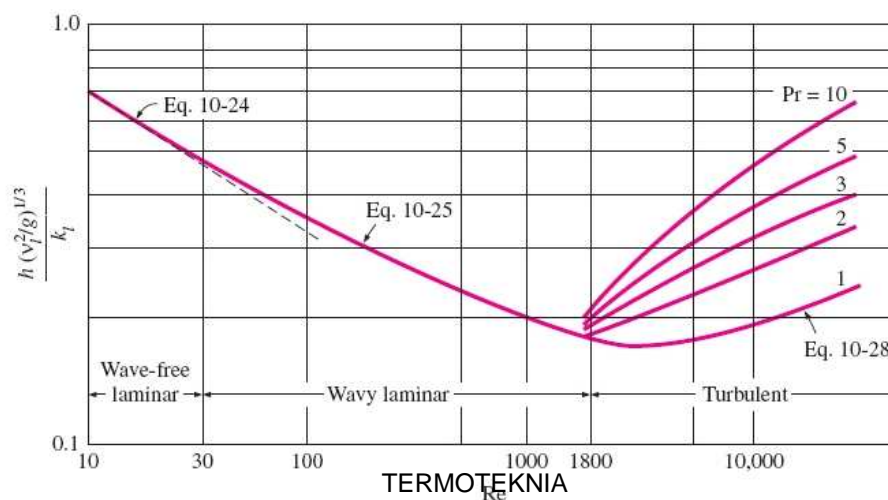
## GERUZA-ERA KO KONDENTSATZIOKO BERO-TRANSFERENTZIAREN KORRELAZIOAK

### 1 – Xafla bertikalak – Fluxu turbulentua

Labuntsov

$$h_{vert, turb} = \frac{k_l Re}{8750 + 58 Pr^{-0.5} (Re^{0.75} - 253)} \left( \frac{g}{v_l^2} \right)^{1/3} \quad Re > 1800 \quad \rho_v \ll \rho_l$$

$$Re_{vert, turb} = \left[ \frac{0.0690 L k_l Pr^{0.5} (T_{sat} - T_s)}{\mu_l h_{fg}^*} \left( \frac{g}{v_l^2} \right)^{1/3} - 151 Pr^{0.5} + 253 \right]^{4/3}$$

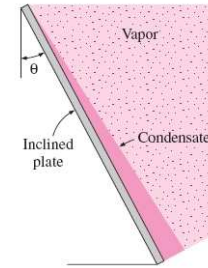


## GERUZA-ERA KO KONDENTSAZIOKO BERO-TRANSFERENTZIAREN KORRELAZIOAK

## 2 – Xafla inklinatuak

$$g = g \cdot \cos \theta \Rightarrow h_{inclined} = h_{vert} (\cos \theta)^{1/4}$$

(Laminarra)

3 – Hodi bertikalak Baldin  $D \gg \delta$  xafla laueko korrelazio bera erabili

## 4 – Hodi horizontalak eta esferak

$$h_{horiz} = 0.729 \left[ \frac{g \rho_l (\rho_l - \rho_v) h_{fg}^* k_l^3}{\mu_l (T_{sat} - T_s) D} \right]^{1/4} \Rightarrow \frac{h_{vert}}{h_{horiz}} = 1.29 \left( \frac{D}{L} \right)^{1/4}$$

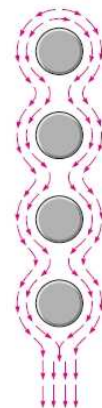
$$h_{sph} = 0.815 \left[ \frac{g \rho_l (\rho_l - \rho_v) h_{fg}^* k_l^3}{\mu_l (T_{sat} - T_s) D} \right]^{1/4} \quad L = 2.77 D$$

## 10.5 – GERUZA-ERA KO KONDENTSAZIOA

## GERUZA-ERA KO KONDENTSAZIOKO BERO-TRANSFERENTZIAREN KORRELAZIOAK

## 4 – Hodi multzo horizontalak

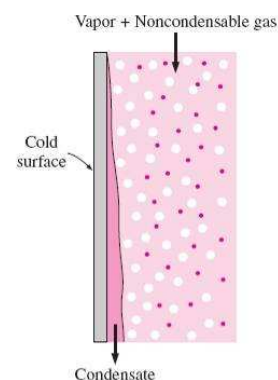
$$h_{horiz, N} = 0.729 \left[ \frac{g \rho_l (\rho_l - \rho_v) h_{fg}^* k_l^3}{\mu_l (T_{sat} - T_s) N D} \right]^{1/4} = \frac{1}{N^{1/4}} h_{horiz, 1 tubo}$$



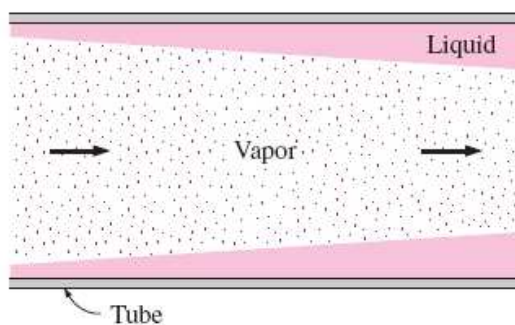
## LURRUN ABIADURA EFEKTUA

Baldin  $V_{lurrun}$  beherantz  $\rightarrow V_{likido} \uparrow \rightarrow \delta \downarrow \rightarrow Q \uparrow$   
 Baldin  $V_{lurrun}$  gorantz  $\rightarrow V_{likido} \downarrow \rightarrow \delta \uparrow \rightarrow Q \downarrow$

## GAS KONDENTSAEZINAK KONDENTSA DOREETAN







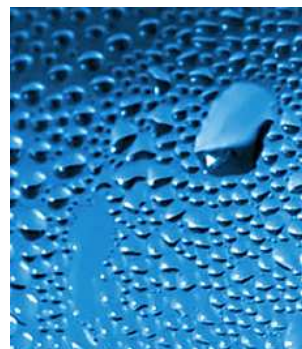
Baldin  $Re_{vapor} = \left( \frac{\rho_v V_v D}{\mu_v} \right)_{inlet} < 35000$

**Chato**  $h_{internal} = 0.555 \left[ \frac{g \rho_l (\rho_l - \rho_v) k_l^3}{\mu_l (T_{sat} - T_s)} \left( h_{fg} + \frac{3}{8} c_{pl} (T_{sat} - T_s) \right) \right]^{1/4}$

## 10.7 – TANTA-ERAKO KONDENTSATZIOA

Gehigarri kimikoak

Metal nobleak



**Griffith**  
(Lurruna + Kupre gainazala)  $h_{dropwise} = \begin{cases} 51104 + 2044 \cdot T_{sat} & 22^\circ \text{C} < T_{sat} < 100^\circ \text{C} \\ 255310 & T_{sat} > 100^\circ \text{C} \end{cases}$

## 10.8 – IRAKATSIKO EZ DIREN ATALAK