

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-lurrun faseartea

Lurrun-presioa <math>P < P_{sat}</math> ($T_{jariakin}$)

Irakitea

Solido-likido faseartea

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

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

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

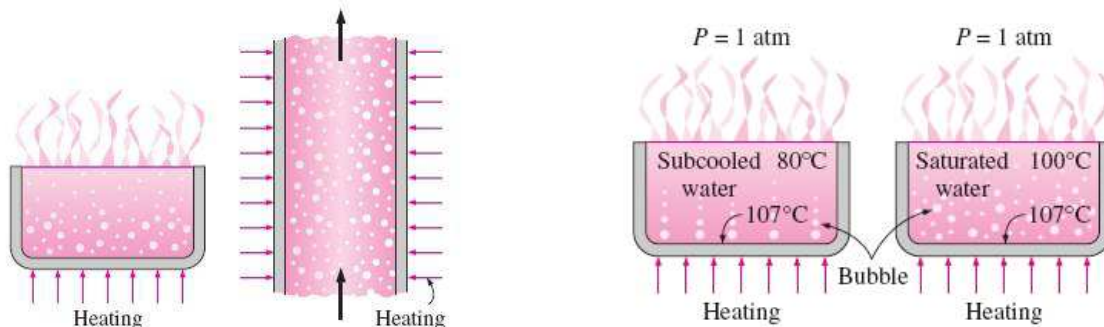
Konbekzio behartu eta naturala (fase bakarra) Propietateak: μ , ρ , k eta c_p

Irakitea Propietateak: μ , ρ , k eta c_p (likido eta lurrunarena).

h_{fg} = Lurruntze-bero sorra.

σ = Gainazal-tentsioa.

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



Tanga-erako irakitea

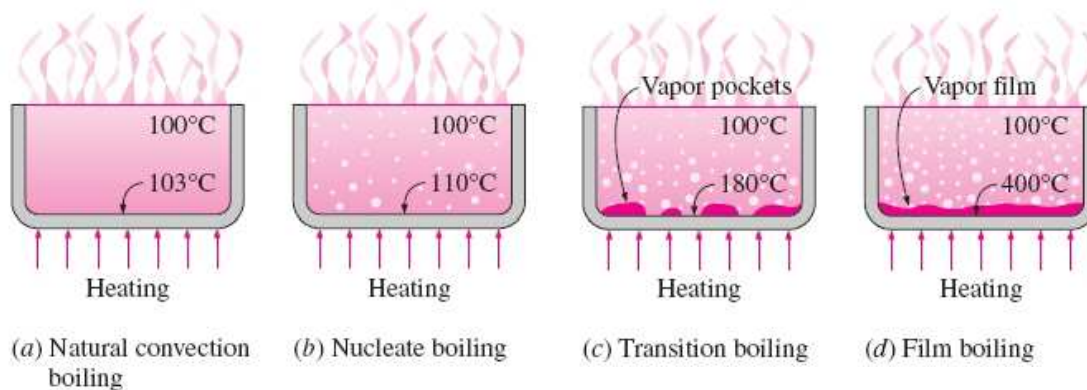
Fluxu-erako irakitea (irakitea konbekzio behartuan)

Irakite azpihoztua (lokala)

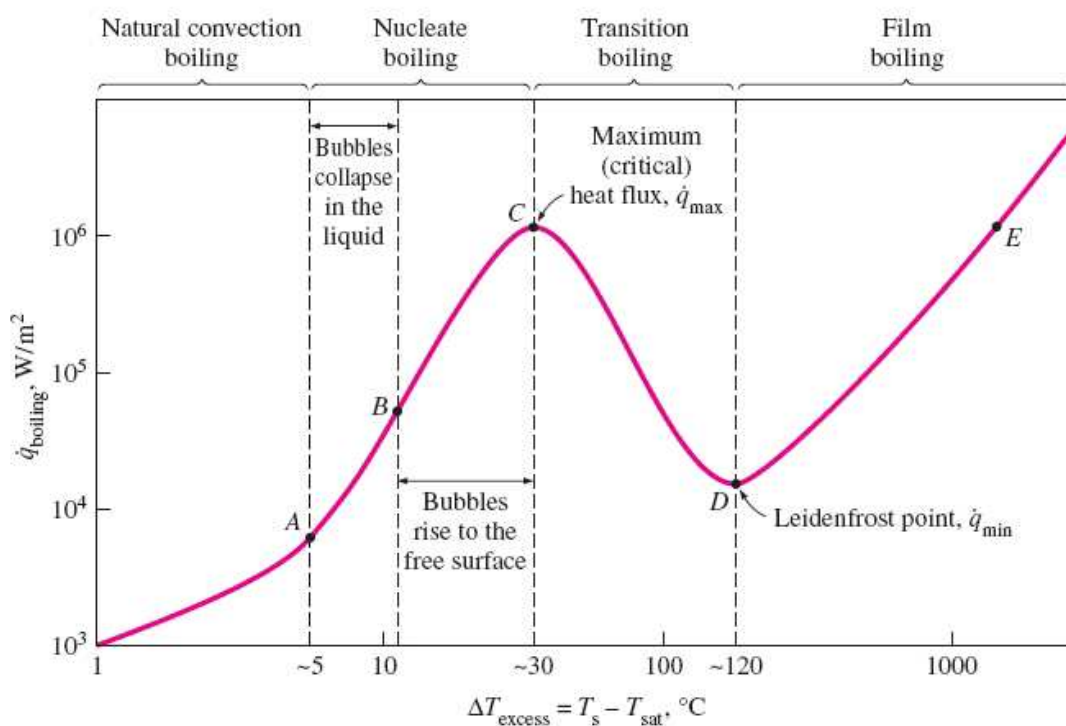
Irakite ase (globala)

IRAKITE-ERREGIMENAK ETA IRAKITE-KURBA

Irakite prozesuak ΔT_{excess} -ren arabera forma desberdinak har ditzake



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:

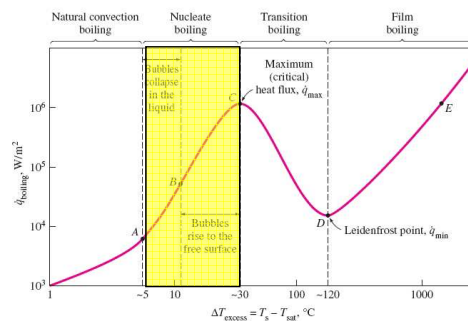
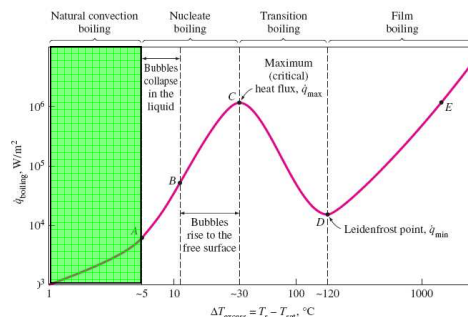
A-B: Burbuila isolatuak.

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.

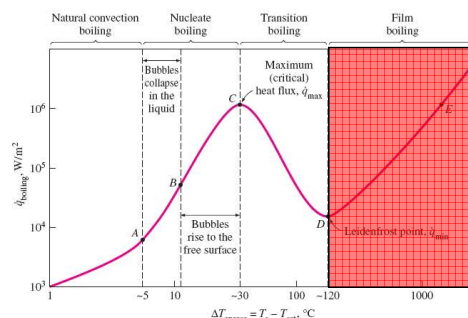
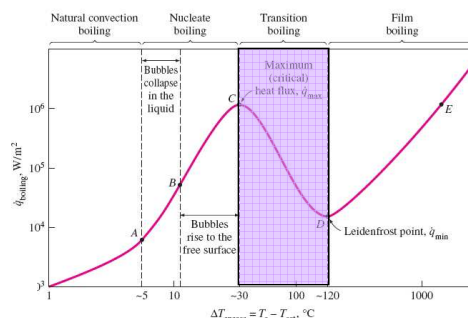
Irakite nukleatutik → Geruza-erako irakitera.

Geruza-erako irakitea (D puntutik aurrera)

Lurrun geruza jarraitu eta egonkorra.

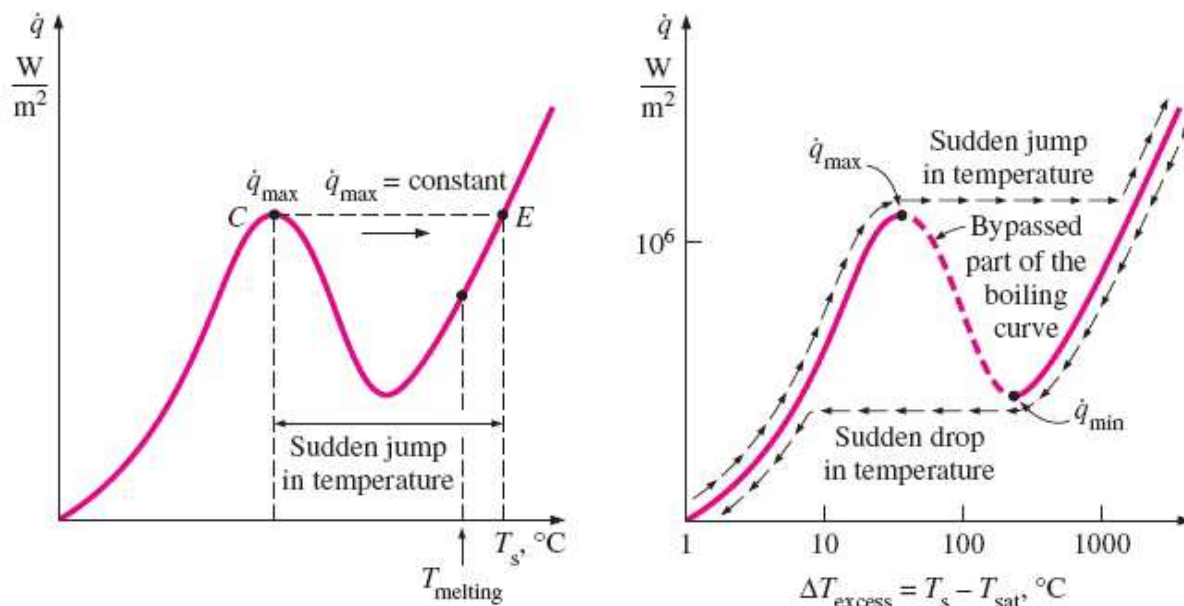
D: Leidenfrost puntua \dot{q}_{min}

Lurrun-geruzan erradiazio bero-transferentzia.



IRAKITE-ERREGIMENAK ETA IRAKITE-KURBA

Irakite-kurba errealak



TANGA-ERA KO KORRELAZIOAK

IRAKITE-PROZESUKO

BERO-TRANSFERENTZIAKO

Konbekzio naturaleko irakitea → 9. GAIA

Irakite nukelatua

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

Errorea:
 ± 100 % q-n
 ± 30 % ΔT_{excess} -n

- $\dot{q}_{nucleate}$ = nucleate boiling heat flux, W/m²
- μ_l = viscosity of the liquid, kg/m · s
- h_{fg} = enthalpy of vaporization, J/kg
- g = gravitational acceleration, m/s²
- ρ_l = density of the liquid, kg/m³
- ρ_v = density of the vapor, kg/m³
- σ = 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
KORRELAZIOAK**

Surface tension of liquid–vapor interface for water

T, °C	σ, 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, σ, N/m* (T in °C)
Ammonia, –75 to –40°C:	0.0264 + 0.000223T
Benzene, 10 to 80°C:	0.0315 – 0.000129T
Butane, –70 to –20°C:	0.0149 – 0.000121T
Carbon dioxide, –30 to –20°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 ¹	$18.9K_1$	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	$0.15 < L^* < 4.26$

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

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)

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

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

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

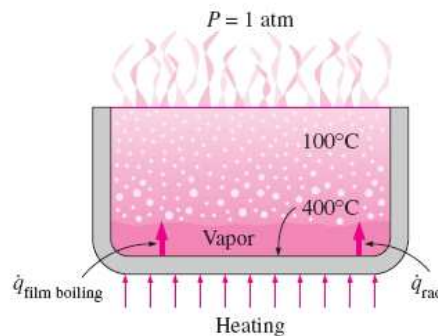
TANGA-ERA KO
KORRELAZIOAK

IRAKITE-PROZESUKO

BERO-TRANSFERENTZIAKO

Geruza-erako irakitea

• $T_s \uparrow \rightarrow$ Erradiazioa



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

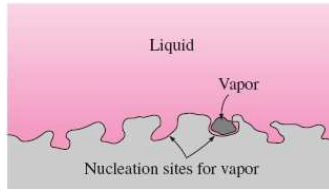
Baldin $\dot{q}_{rad} < \dot{q}_{film}$

Bromley

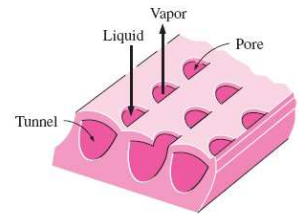
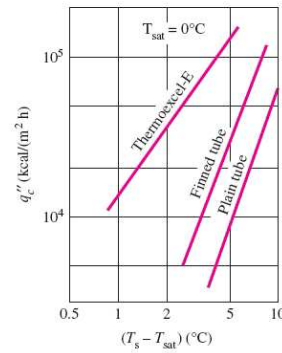
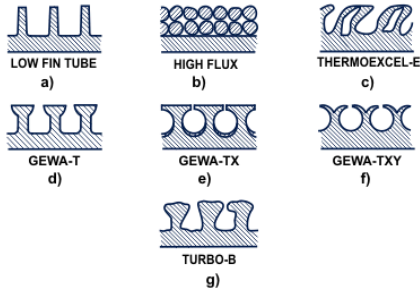
$$\dot{q}_{total} = \dot{q}_{film} + \frac{3}{4} \dot{q}_{rad}$$

TANGA-ERA KO IRAKITE-PROZESUKO BERO-TRANSFERENTZIA INDARTZE A

Zimurtasuna eta hautsa (gainazal irregulartasunak)



Bero-transferentzia hobetzen duten gainazalak



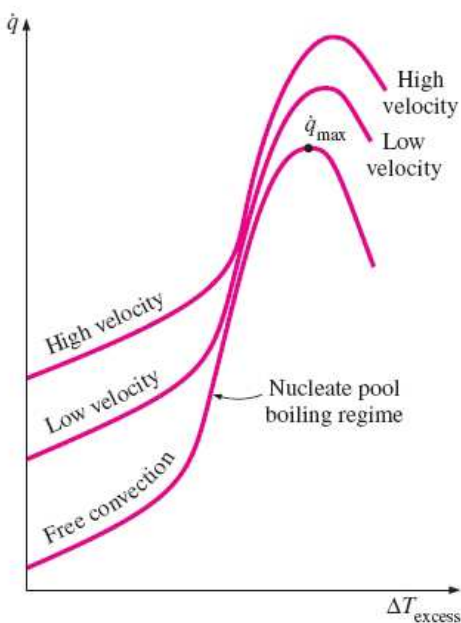
Mekanikoki eraginda

Gainazal-bibrazioa

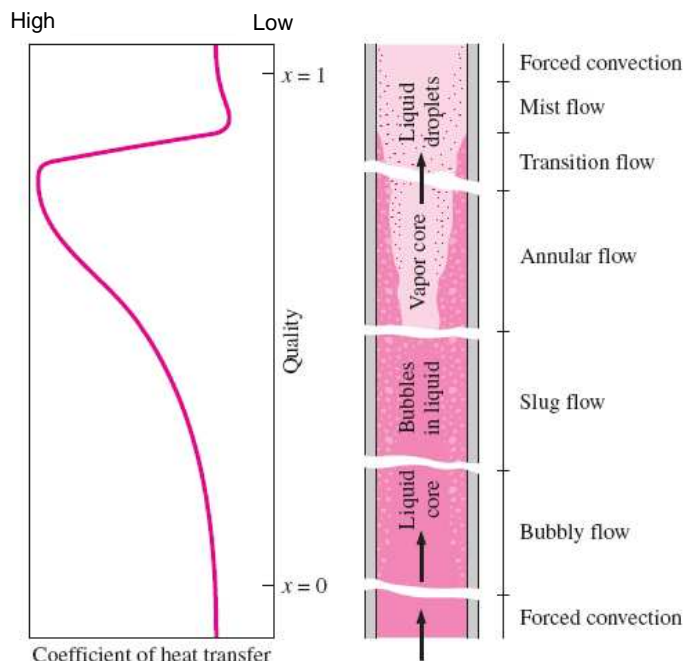
10.3 – FLUXU-ERA KO IRAKITEA

Konbekzio behartua eta tanga-erako irakitearen efektu bateratuak

Kanpo fluxu-erako irakitea



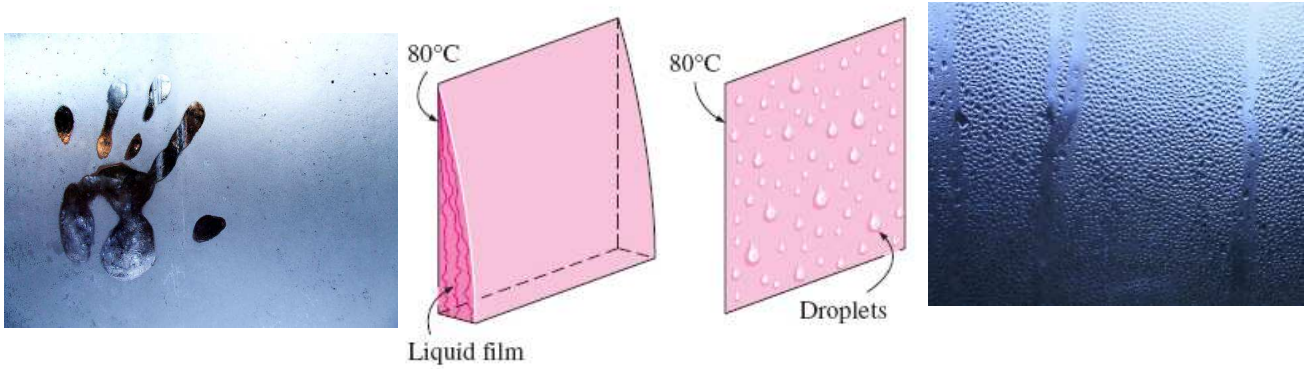
Barne fluxu-erako irakitea



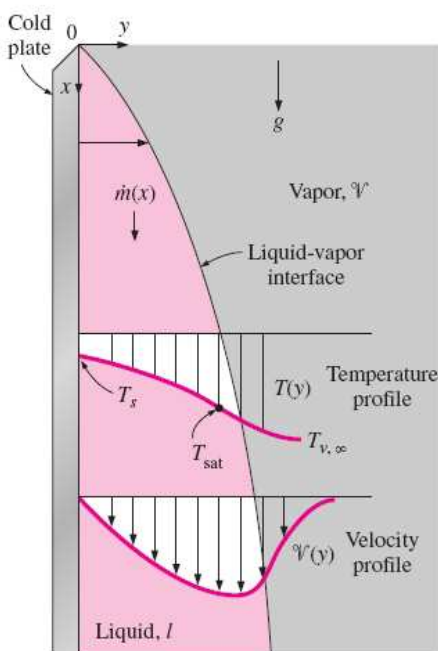
Estimazio gordina:

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

- Lurrin baten temperatura haren T_{sat} -tik behera jaistean.
- Gainazal solidoen gaineko kondentsazioa.
- Bi motakoak: **Geruza-erako kondentsazioa** **Tanta-erako kondentsazioa**



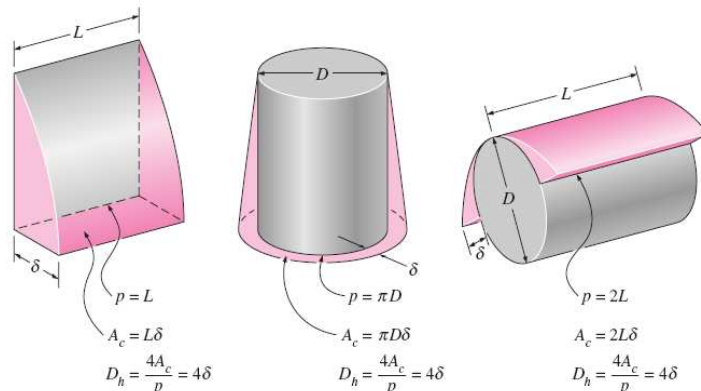
10.5 – GERUZA-ERAKO KONDENTSAZIOA



	T	V
Solido – likido faseartea	T_s	0
Likido – lurrin faseartea	T_{sat}	V_{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 temperatura batera azpizozten da.

Rohsenow
(Lurrunketa bero sorra eraldatua)

$$h_{fg}^* = h_{fg} + 0,68c_{pl}(T_{sat} - T_s)$$

T_v temperatura bateko lurrun gainberotuan:

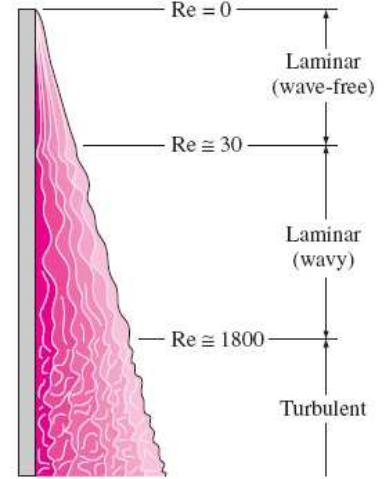
$$h_{fg}^* = h_{fg} + 0,68c_{pl}(T_{sat} - T_s) + c_{pv}(T_v - T_{sat})$$

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

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

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

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



GERUZA-ERA KO KONDENTSATZIOKO BERO-TRANSFERENTZIAREN KORRELAZIOAK

1 – Xafila bertikalak – Fluxu laminarra

T_s eta T_{sat} konstanteak. Kondentsatuan aldaketa lineala.

Bero-transferentzia eroapen bidezkoa.

Lurrunaren abiadura txikia (arrasterik gabe)

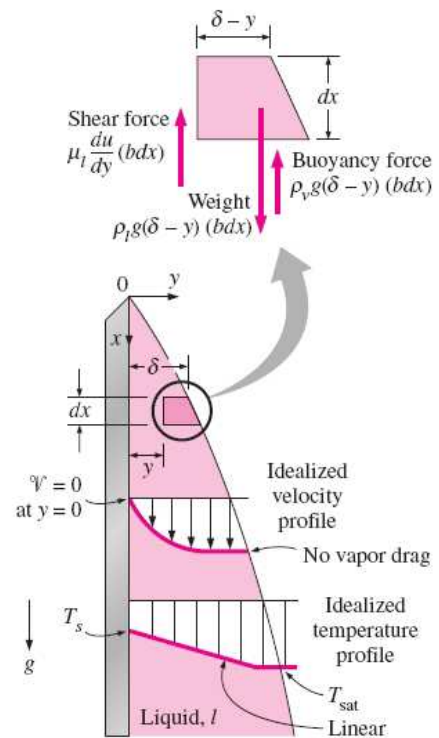
Kondentsatu-fluxu laminarra eta propietateak konstanteak.

Kondentsatu-geruzaren azelerazio baztergarria.

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

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

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



GERUZA-ERA KO KONDENTSATZIOKO BERO-TRANSFERENTZIAREN KORRELAZIOAK

1 – Xafla bertikalak – Fluxu laminarra

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

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

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

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

$$h_{vert} = \frac{1}{L} \int_0^L h_x dx = \frac{4}{3} h_{x=L} \Rightarrow h = 0,943 \left[\frac{g \rho_l (\rho_l - \rho_v) h_{fg} k_l^3}{\mu_l (T_{sat} - T_s) L} \right]^{1/4}$$



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

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

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

$$h_{vert} \cong 1,47 k_l \text{Re}^{-1/3} \left(\frac{g}{v_l^2} \right)^{1/3} \quad 0 < \text{Re} < 30$$

$$\rho_v \ll \rho_l$$



GERUZA-ERA KO KONDENTSATZIO KO BERO-TRANSFERENTZAREN KORRELAZIOAK

1 – Xaf la bertikalak – Fluxu laminar izurtua

Kutateladze

$$h_{vert,wavy} = \frac{k_l Re}{1,08 Re^{1,22} - 5,2} \left(\frac{g}{v_l^2} \right)^{1/3} \quad 30 < Re < 1800$$

$$\rho_v \ll \rho_l$$

$$h_{vert,wavy} = 0,8 Re^{0,11} h_{vert}$$

$$Re_{vert,wavy} = \left[4,81 + \frac{3,70 L k_l (T_{sat} - T_s)}{\mu_l h_{fg}^*} \left(\frac{g}{v_l^2} \right)^{1/3} \right]^{0,820} \quad \rho_v \ll \rho_l$$

GERUZA-ERA KO KONDENTSATZIO KO BERO-TRANSFERENTZAREN KORRELAZIOAK

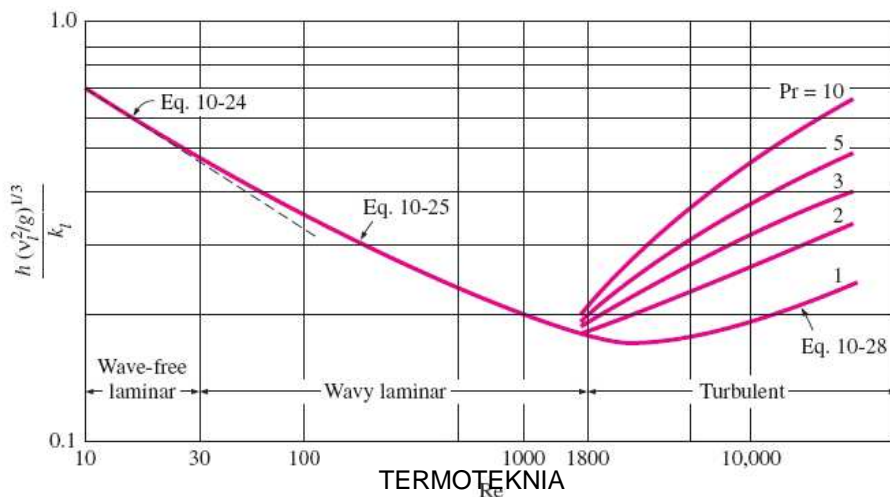
1 – Xaf la bertikalak – Fluxu turbulentu a

Labuntsov

$$h_{vert,turb} = \frac{k_l Re}{8750 + 58 Pr^{-0,5} (Re^{0,75} - 253)} \left(\frac{g}{v_l^2} \right)^{1/3} \quad Re > 1800$$

$$\rho_v \ll \rho_l$$

$$Re_{vert,turb} = \left[\frac{0,0690 L k_l Pr^{0,5} (T_{sat} - T_s)}{\mu_l h_{fg}^*} \left(\frac{g}{v_l^2} \right)^{1/3} - 151 Pr^{0,5} + 253 \right]^{4/3}$$

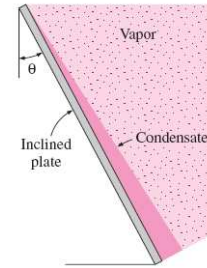


GERUZA-ERA KO KONDENTSATZIOKO BERO-TRANSFERENTZIAREN KORRELAZIOAK

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

$$h_{horiz} = 0,729 \left[\frac{g \rho_l (\rho_l - \rho_v) h_{fg}^* k_l^3}{\mu_l (T_{sat} - T_s) D} \right]^{1/4} \Rightarrow \frac{h_{vert}}{h_{horiz}} = 1,29 \left(\frac{D}{L} \right)^{1/4}$$

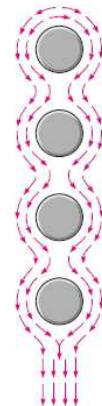
$$L = 2,77 D$$

$$h_{sph} = 0,815 \left[\frac{g \rho_l (\rho_l - \rho_v) h_{fg}^* k_l^3}{\mu_l (T_{sat} - T_s) D} \right]^{1/4}$$

GERUZA-ERA KO KONDENTSATZIOKO BERO-TRANSFERENTZIAREN KORRELAZIOAK

4 – Hodi multzo horizontalak

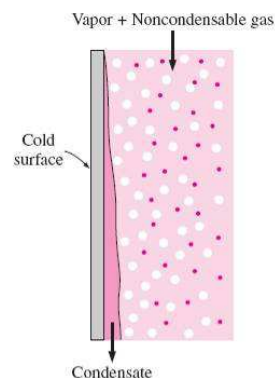
$$h_{horiz, N} = 0,729 \left[\frac{g \rho_l (\rho_l - \rho_v) h_{fg}^* k_l^3}{\mu_l (T_{sat} - T_s) ND} \right]^{1/4} = \frac{1}{N^{1/4}} h_{horiz, 1tubo}$$

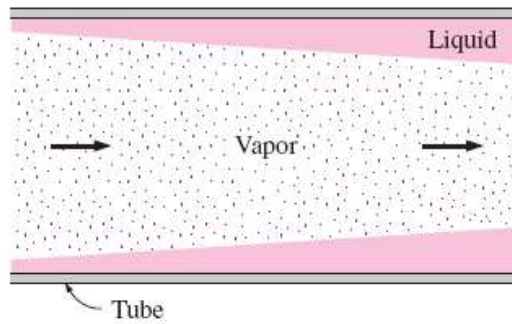


LURRUN ABIADURA EFEKTUA

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 KONDENTSADOREETAN





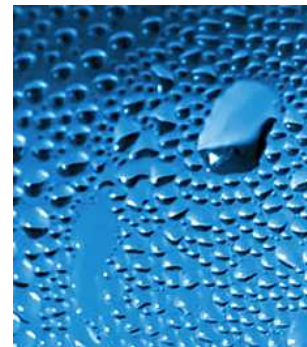
Baldin $Re_{vapor} = \left(\frac{\rho_v V_v D}{\mu_v} \right)_{inlet} < 35000$

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-ERA KO 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