HEAT TRANSFER

[CH21204]

April 05, 2023

BOILING & CONDENSATION

- **Boiling** is a liquid-to-vapor phase change process just like **evaporation**
- **Evaporation** occurs at the **liquid–vapor interface** when the vapor pressure is less than the saturation pressure of the liquid at a given temperature
- Water will evaporate to air at 20°C and 60% relative humidity.
    - saturation pressure of water at 20°C is 2.3 kPa
    - vapor pressure of air at 20°C and 60% relative humidity is 1.4 kPa
- **Evaporation** involves no bubble formation or bubble motion.
- **Boiling** occurs at the **solid–liquid interface** when a liquid is brought into contact with a surface maintained at a temperature sufficiently above the saturation temperature of the liquid.
- Liquid water in contact with a solid surface at 110°C will boil since the saturation temperature of water at 1 atm is 100°C.

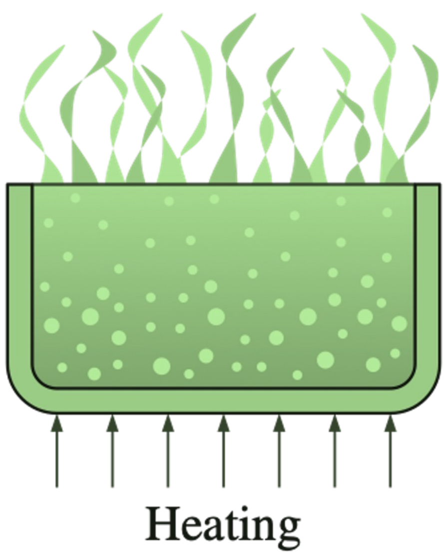
- The boiling process is characterized by the rapid formation of vapor bubbles at the solid–liquid interface that detach from the surface when they reach a certain size and attempt to rise to the free surface of the liquid.

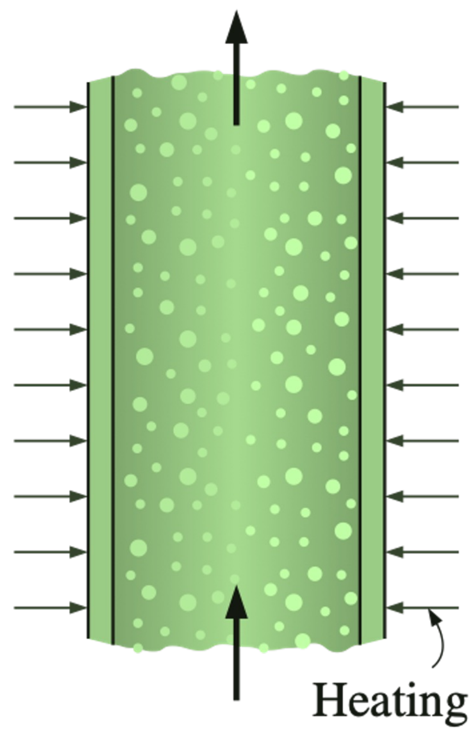
$$\dot{q}_{\text{boiling}} = h(T_s - T_{\text{sat}}) = h\Delta T_{\text{excess}} \qquad (\text{W/m}^2)$$

- **Excess temperature** represents the excess of the surface above the saturation temperature of the fluid.
- Depend on the **latent heat of vaporization (h_{fg})** of the fluid and the **surface tension at the liquid–vapor interface**, in addition to **the properties of the fluid in each phase**.
- **h_{fg}** is the energy absorbed as a unit mass of liquid vaporizes at a specified temperature or pressure and is the **primary quantity of energy** transferred during boiling heat transfer.

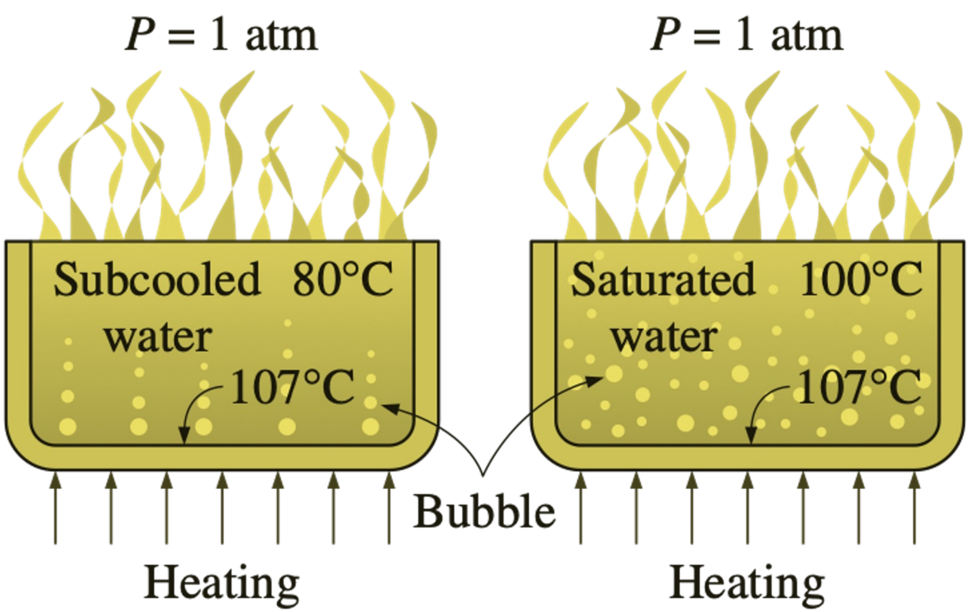
- Bubbles owe their existence to the surface-tension at the liquid–vapor interface due to the attraction force on molecules at the interface toward the liquid phase.
- The surface tension decreases with increasing temperature and becomes zero at the critical temperature.

Pool boiling

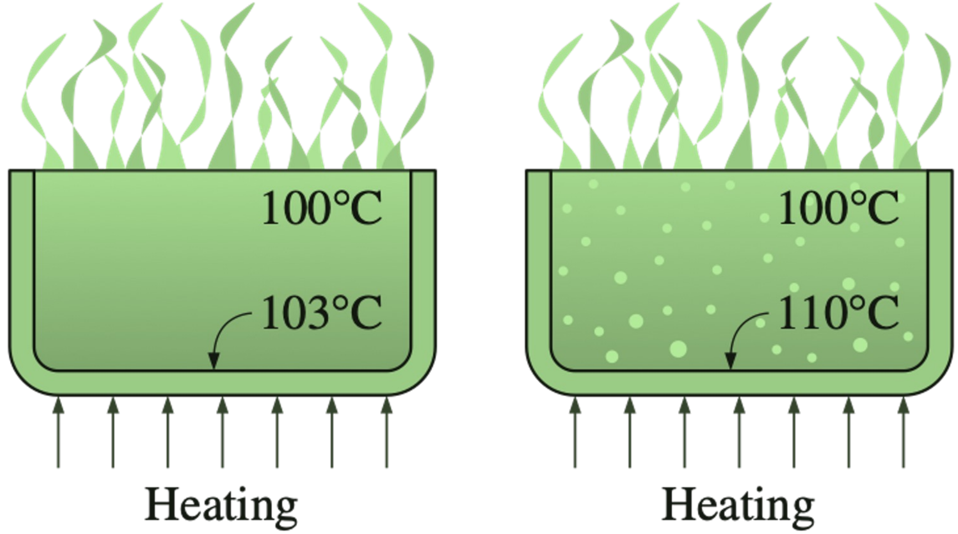




Flow boiling

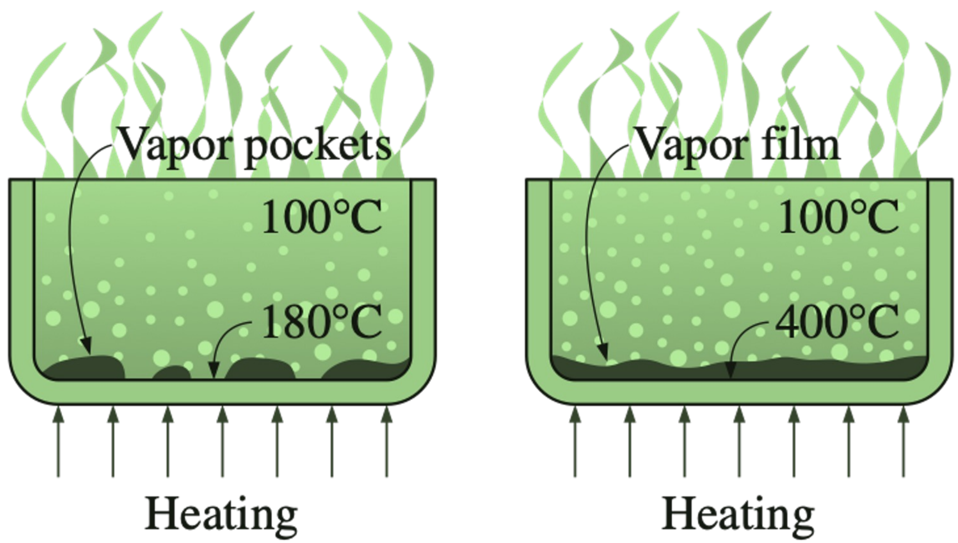


- **Subcooled** (or local) when the temperature of the main body of the liquid is below the saturation temperature



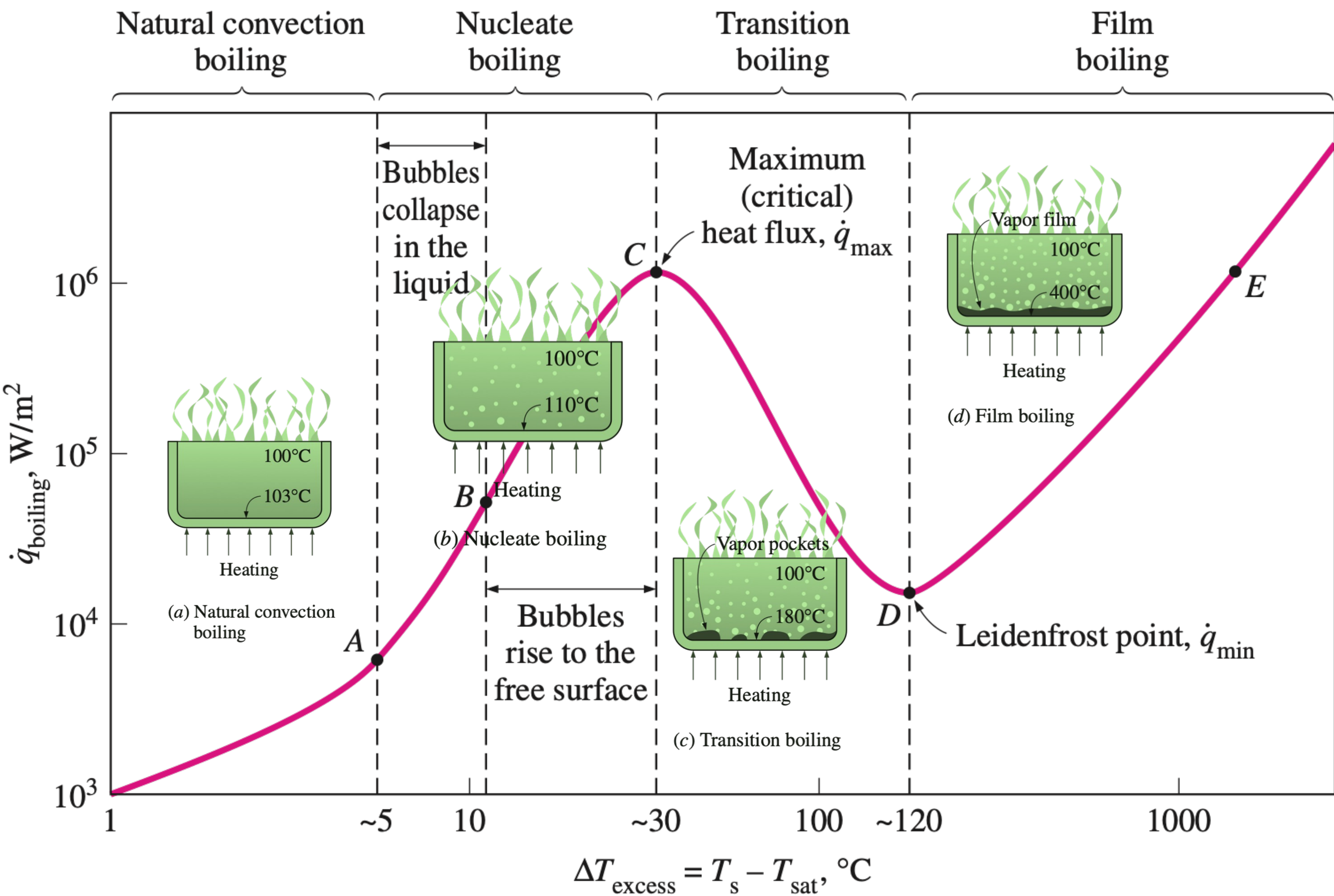
(*a*) Natural convection boiling

(*b*) Nucleate boiling

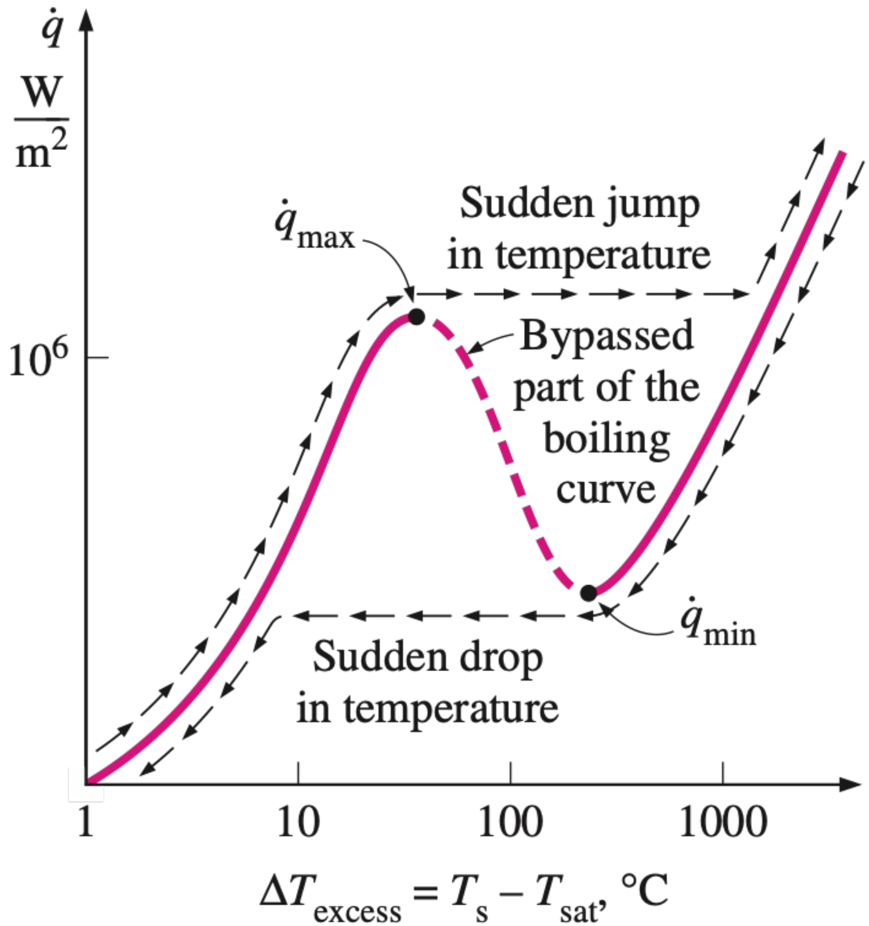


(*c*) Transition boiling

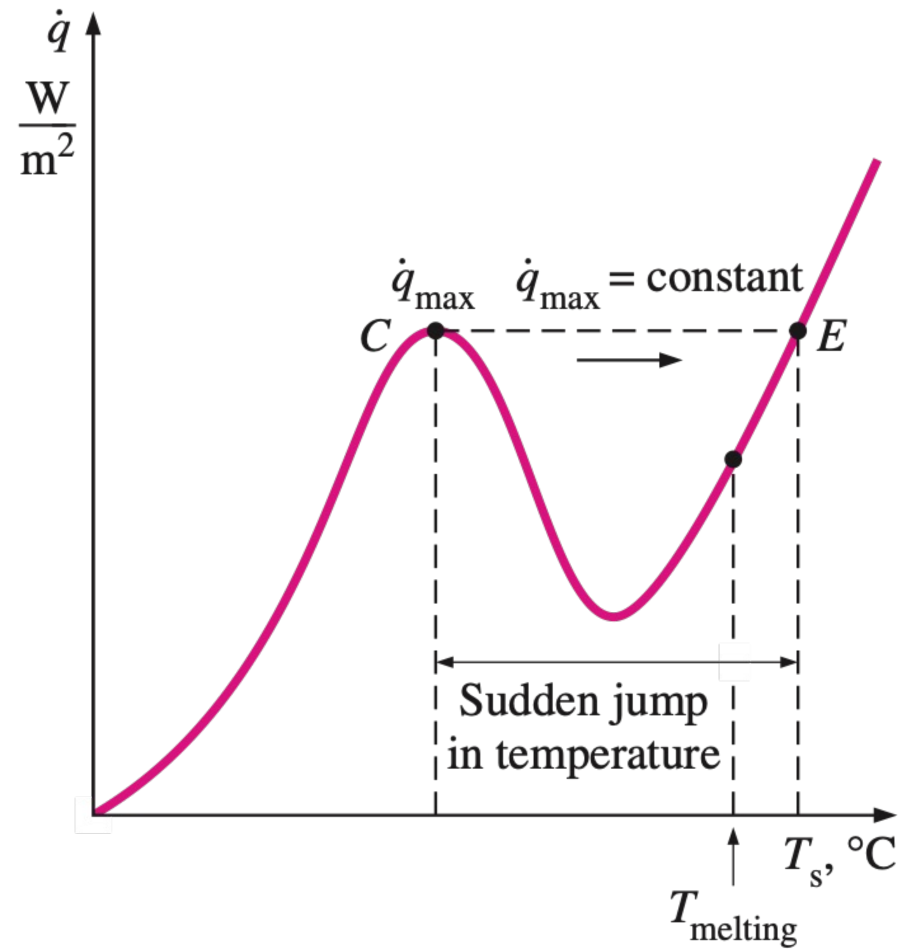
(*d*) Film boiling



Natural convection boiling
Nucleate boiling
Transition boiling
Film boiling
Bubbles collapse in the liquid
Maximum (critical) heat flux, $\dot{q}_{max}$
C
100°C
110°C
Heating
B
(b) Nucleate boiling
Vapor film
100°C
400°C
Heating
(d) Film boiling
E
100°C
103°C
Heating
(a) Natural convection boiling
A
Bubbles rise to the free surface
Vapor pockets
100°C
180°C
Heating
(c) Transition boiling
D
Leidenfrost point, $\dot{q}_{min}$
$\dot{q}_{boiling}$, W/m^2
10^6
10^5
10^4
10^3
1
~5
10
~30
100
~120
1000
$\Delta T_{excess} = T_s - T_{sat}$, °C



$\dot{q}$
$\frac{W}{m^2}$
$\dot{q}_{max}$
Sudden jump
in temperature
10^6
Bypassed
part of the
boiling
curve
$\dot{q}_{min}$
Sudden drop
in temperature
1
10
100
1000
$\Delta T_{excess} = T_s - T_{sat}$, °C



$\dot{q}$
$\frac{W}{m^2}$
$\dot{q}_{max}$
$\dot{q}_{max}$ = constant
C
E
Sudden jump
in temperature
T_s, °C
$T_{melting}$

Nucleate Boiling

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

$\dot{q}_{\text{nucleate}}$ = nucleate boiling heat flux, W/m^2
μ_l = viscosity of the liquid, $kg/m \cdot s$
h_{fg} = enthalpy of vaporization, J/kg
g = gravitational acceleration, m/s^2
ρ_l = density of the liquid, kg/m^3
ρ_v = density of the vapor, kg/m^3
σ = surface tension of liquid–vapor interface, N/m
C_{pl} = specific heat of the liquid, $J/kg \cdot °C$
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

Peak Heat Flux

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

Minimum Heat Flux

$$\dot{q}_{\min} = 0.09\rho_v\, h_{fg}\left[\frac{\sigma g(\rho_l - \rho_v)}{(\rho_l + \rho_v)^2}\right]^{1/4}$$