Towards modeling the impact of the aspect ratio in an energy model describing the transient flow boiling crisis at high subcooling

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1. Transient subcooled boiling crisis and nuclear safety

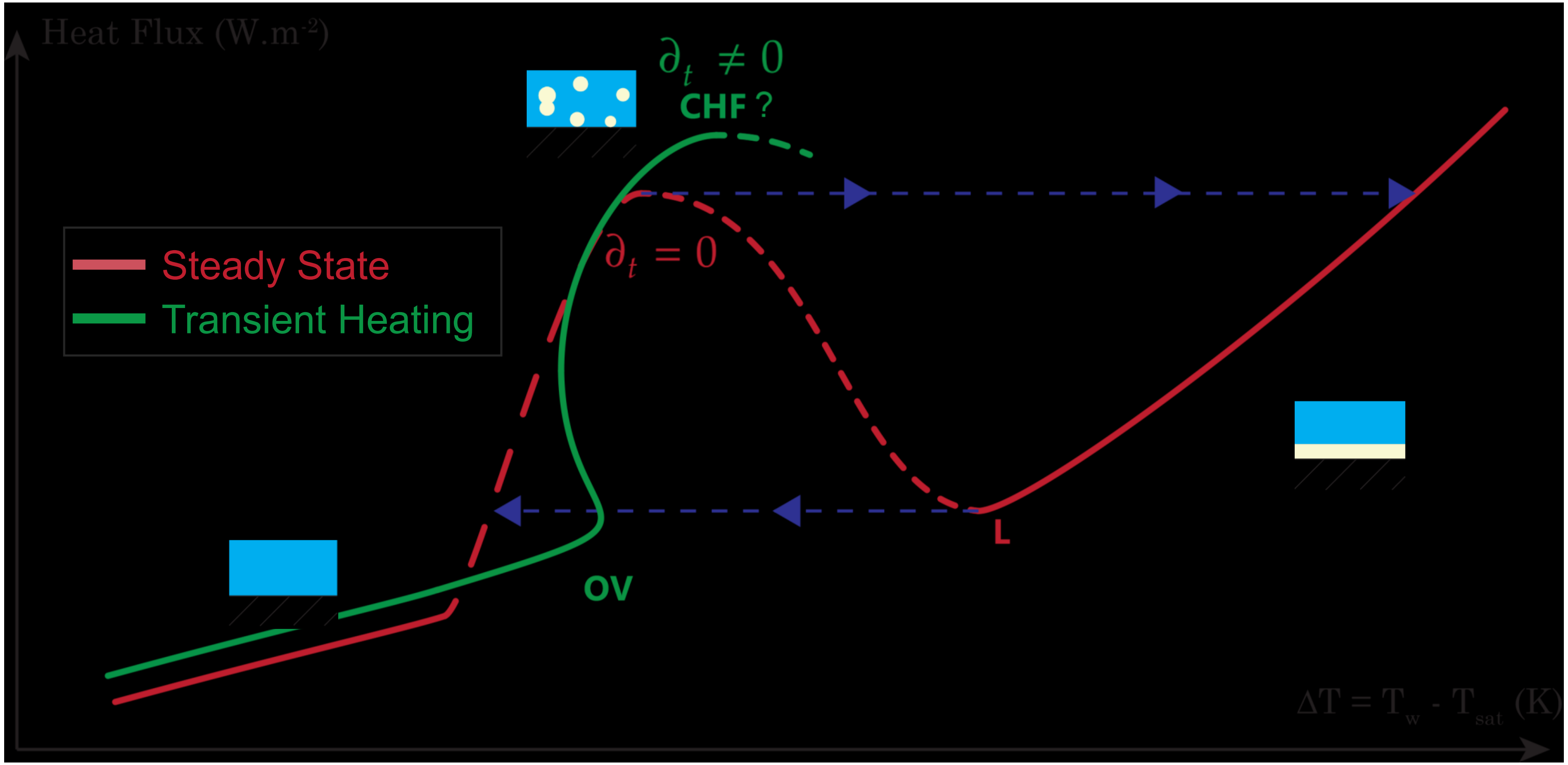
BORAX: A design basis accident for nuclear safety

Pool type research reactor:

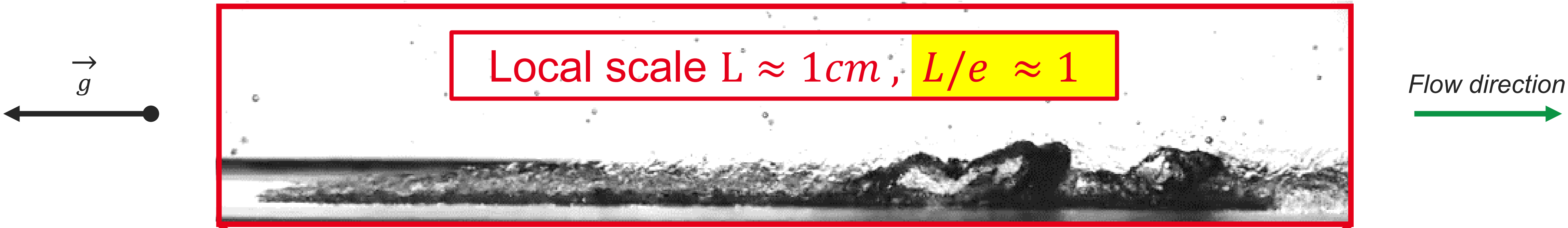
- Coolant at room temperature
- Low pressure (a few bar)
- Highly enriched core

SPERT I Destructive Test conducted at Idaho National Laboratory by the US Atomic Energy Commission ***Spano, (1962)***

Effect of transient heating on the boiling curve of water

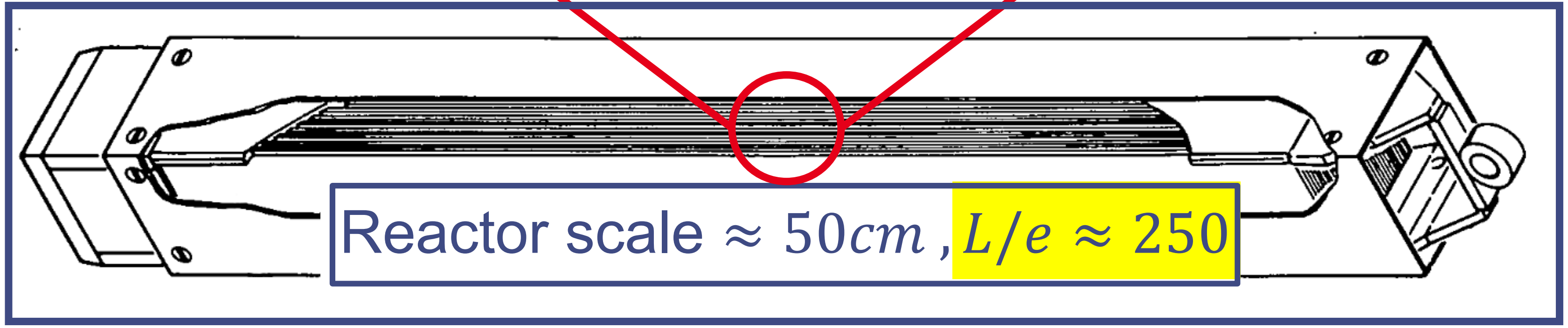


Few mecanistic models exist in the litterature for transient CHF eg: ***Pasamehmetoglu JHT 1990***



Local scale $L \approx 1cm$, $L/e \approx 1$

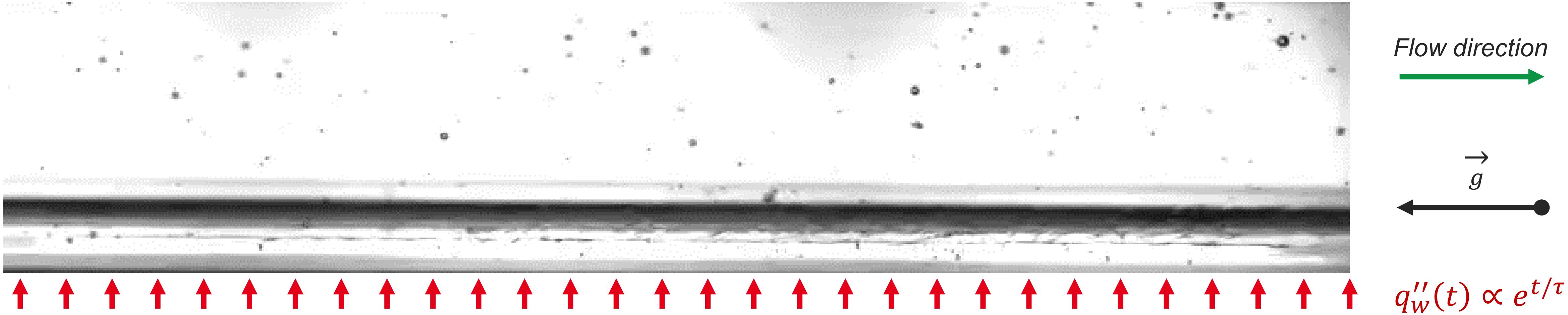
Is the **Homogeneous Mantle Model** ready for **upscaling**?



Reactor scale $\approx 50cm$, $L/e \approx 250$

2. The extended Homogeneous Mantle Model (eHMM)

High speed shadowgraphy of the transient flow boiling crisis at high subcooling (70 000 fps *courtesy of* Nop (2020) [Ph. D. thesis])



Operating conditions	
τ (ms)	100
Re	35 000
ΔT_{sub} (K)	50
P (bar)	1
L/e	4

Phenomenological considerations of the model:

Flow characteristics

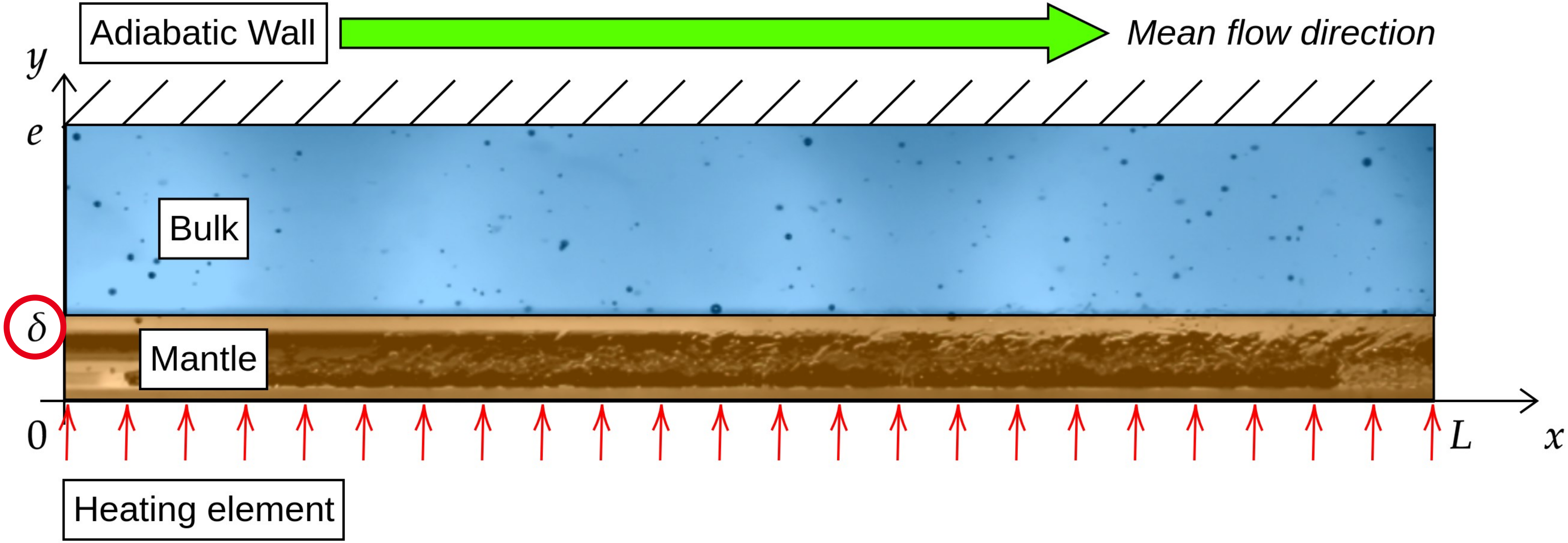
- High Subcooling ($\boldsymbol{\Delta T_{sub} > 25K}$)
- High shear stress (**Re >** $\mathbf{10000}$)

Bubbles characteristics

- Small size ($\mathbf{100\mu m}$)
- Short lifetime ($\mathbf{100\mu s}$)
- Only at the vicinity of the wall

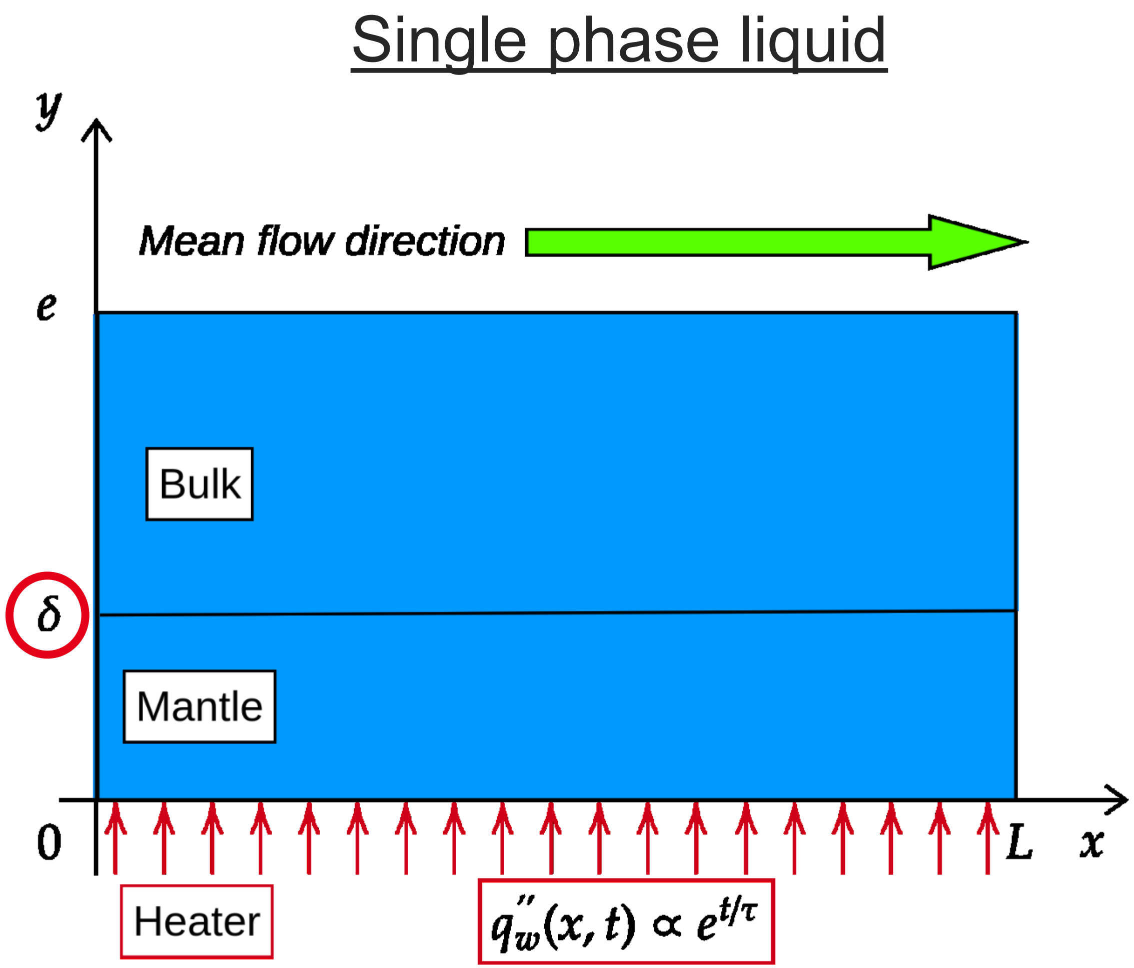
Nucleation and Condensation Cycles

Schematic description of the Homogeneous Mantle Model based on experimental observations



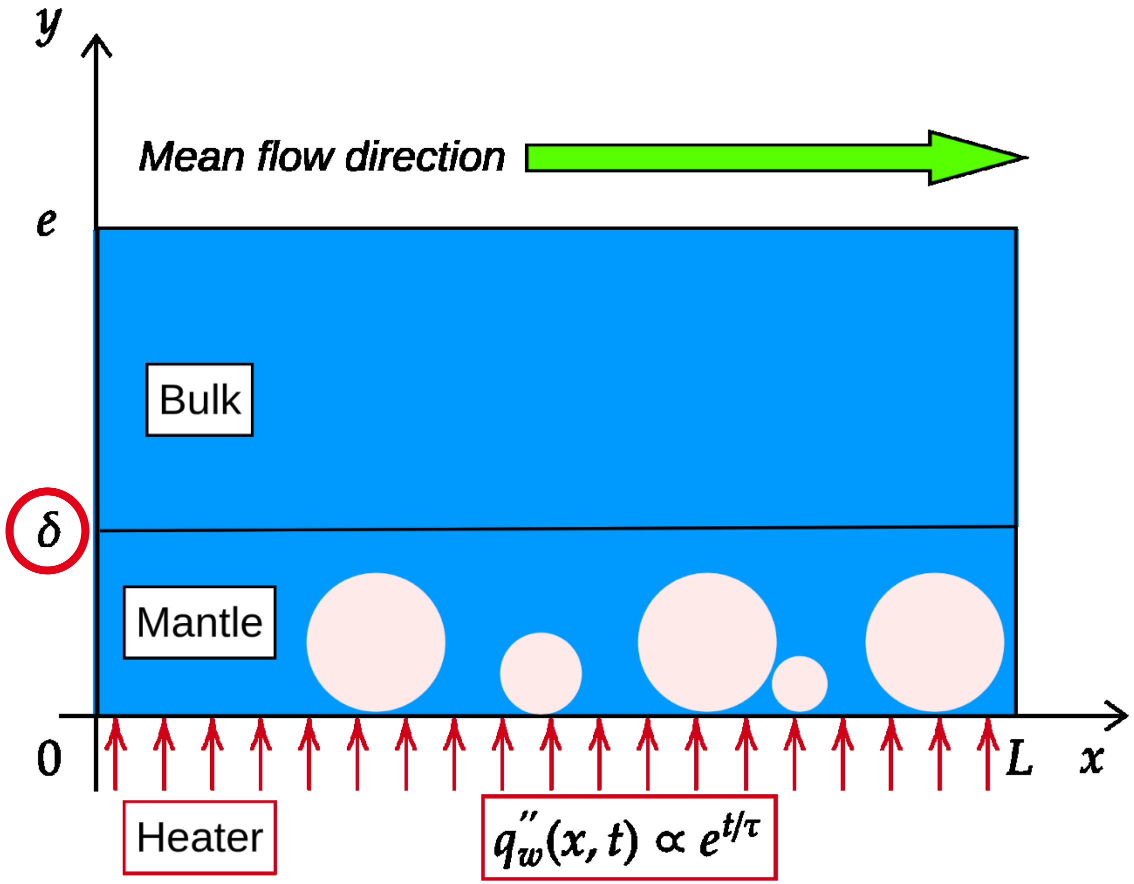
N.B. *The mantle thickness δ is not drawn to scale*

An energetic criterion to describe boiling crisis



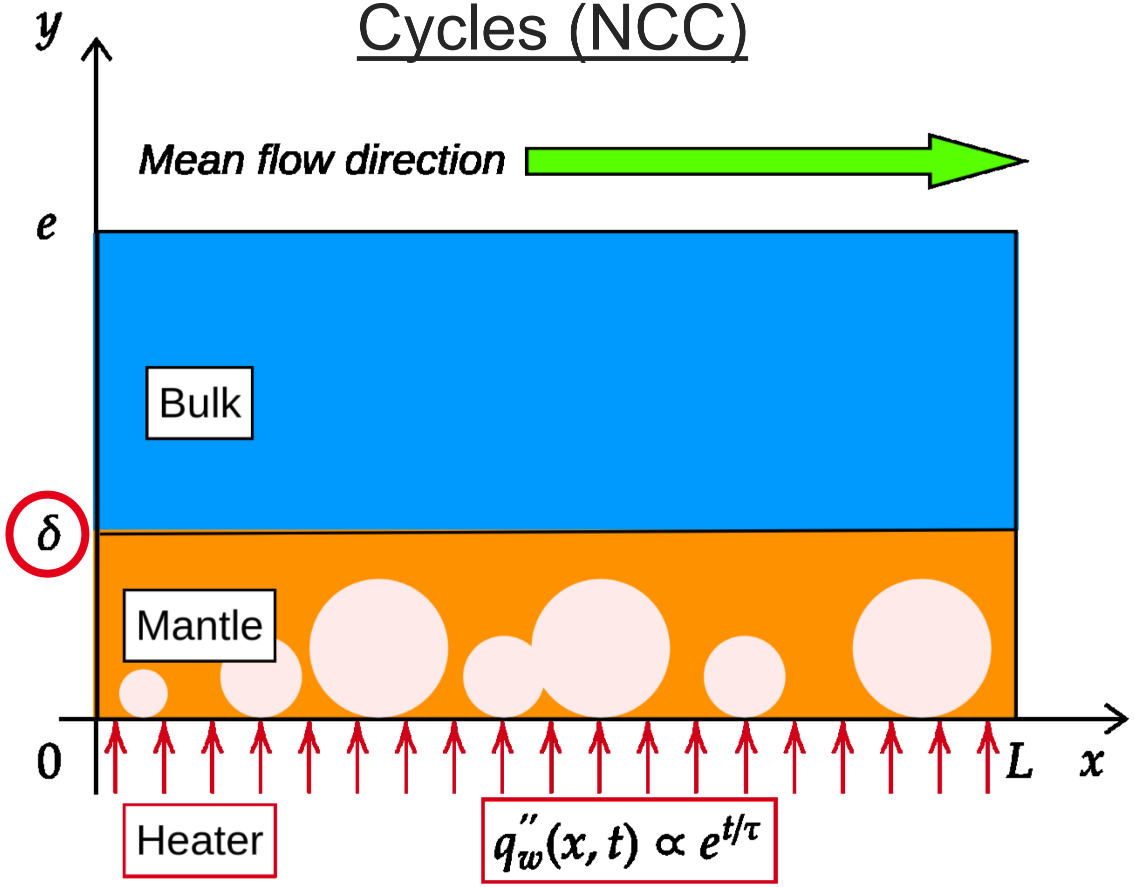
An energetic criterion to describe boiling crisis

Onset on Nucleate Boiling (ONB)



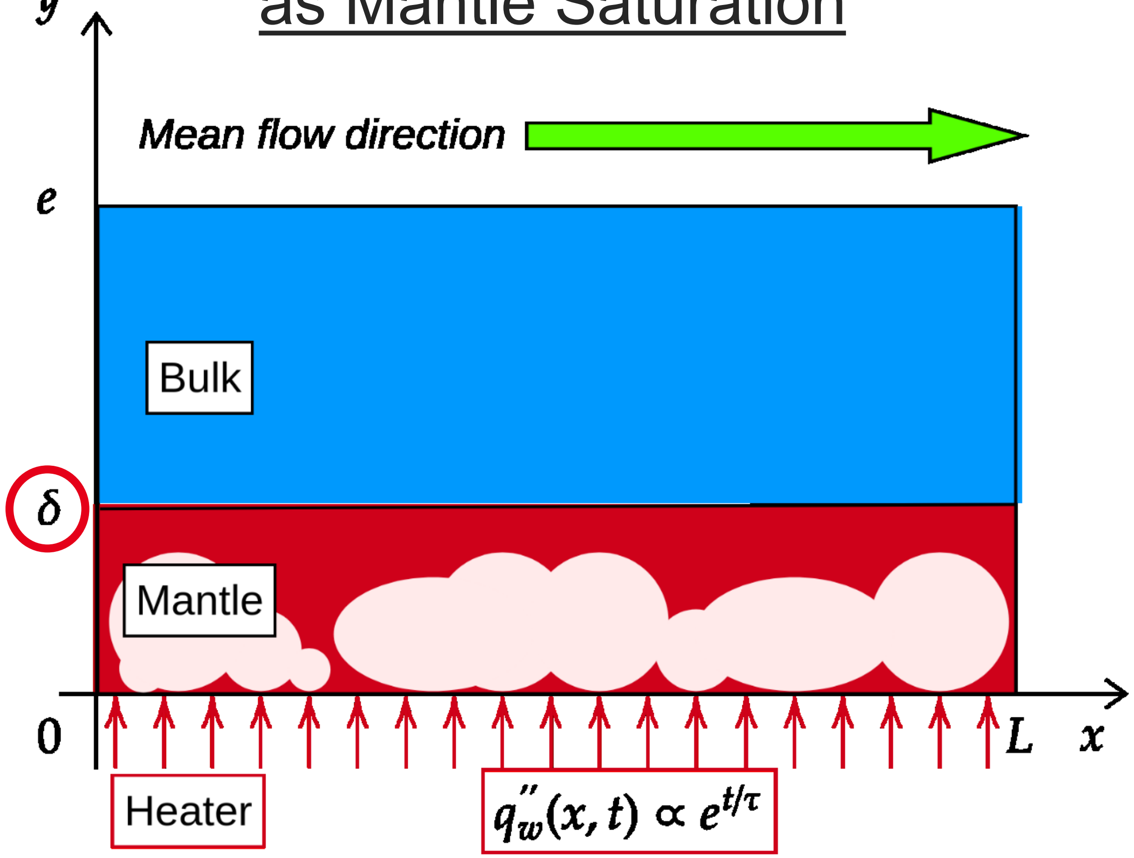
An energetic criterion to describe boiling crisis

Nucleation and Condensation Cycles (NCC)



An energetic criterion to describe boiling crisis

Boiling crisis (Critical Heat Flux) as Mantle Saturation



- Critical Energy of the fluid:

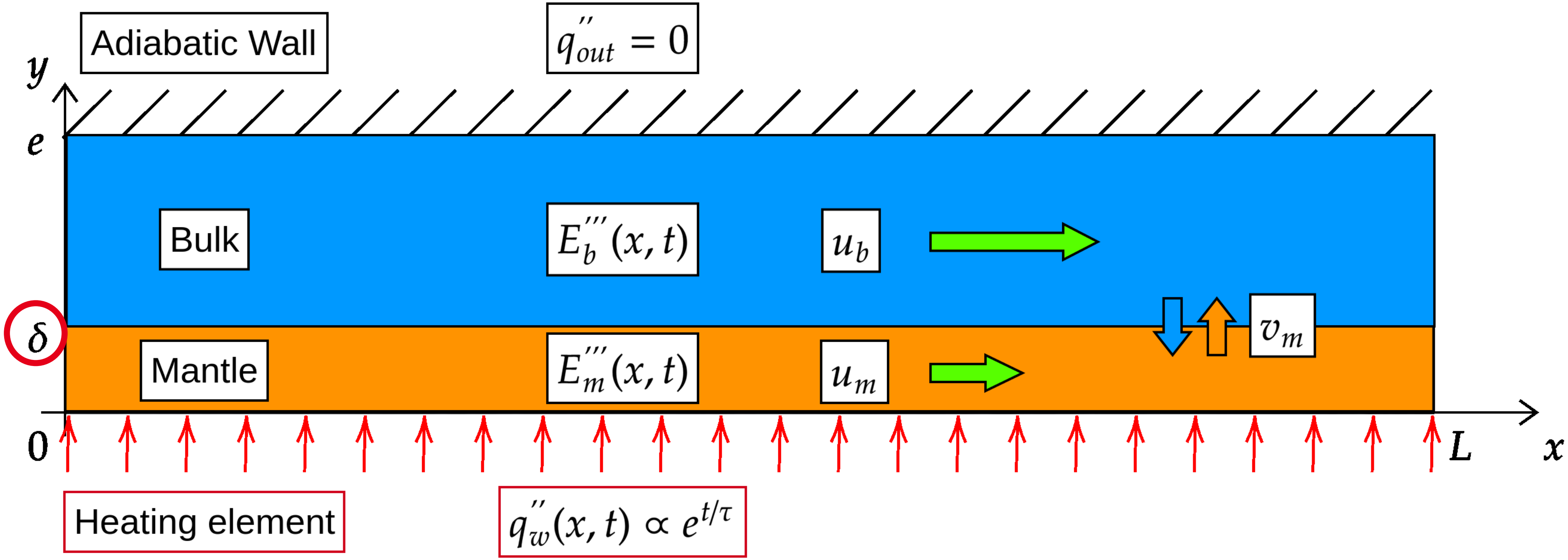
$$E'''_{crit} = \rho_l c_p \Delta T_{sub} \ [J/m^3]$$

$$\Delta T_{sub} = T_{sat}(P) - T_{inlet}$$

- Local boiling crisis condition:

$$E'''_m(x = L, t = t_{CHF}) = E'''_{crit}$$

Mathematical framework of the model



N.B. *The mantle thickness δ is not drawn to scale*

Homogeneous Mantle Model governing equations:

Original model

Nop et al. IJTS, 2021:

Isothermal bulk assumption:

$$T_b = const \;\Rightarrow E_b''' = \text{const}$$

$$\boxed{\frac{\partial E_m'''}{\partial t} + u_m \frac{\partial E_m'''}{\partial x} + \frac{v_m}{\delta} E_m''' = \frac{q_w''}{\delta}}$$

Extended model

To model high L/e configurations we introduced variable bulk temperature

$$\boxed{\begin{cases} \dfrac{\partial E_m'''}{\partial t} + u_m \dfrac{\partial E_m'''}{\partial x} + \dfrac{v_m}{\delta}\left(E_m''' - E_b'''\right) = \dfrac{q_w''}{\delta} \\ \dfrac{\partial E_b'''}{\partial t} + u_b \dfrac{\partial E_b'''}{\partial x} + \dfrac{v_m}{e-\delta}\left(E_b''' - E_m'''\right) = 0 \end{cases}}$$

If the mantle thickness δ is known, we can compute the transient CHF using the model

3. Model results and discussion

Experimental data investigated in this study

Data obtained from international collaboration between CEA and MIT

Data source	**Kossolapov et al. (2020)[IJHMT]**	**Chavagnat et al. (2022)[NURETH19]**
$P\ (bar)$	1	2 - 12
$\Delta T_{sub}(K)$	25 - 75	25 - 160
$G\ (10^3 kg.m^{-2}.s^{-1})$	0.3 – 2	0.9 - 19
$\tau\ (ms)$	5 - 500	5 – 200
L/e	1	1 – 20

The mantle thickness δ is determined using an inverse method applied to experimental data

Model response during transient heating $q''_w(t) \propto e^{t/\tau}$

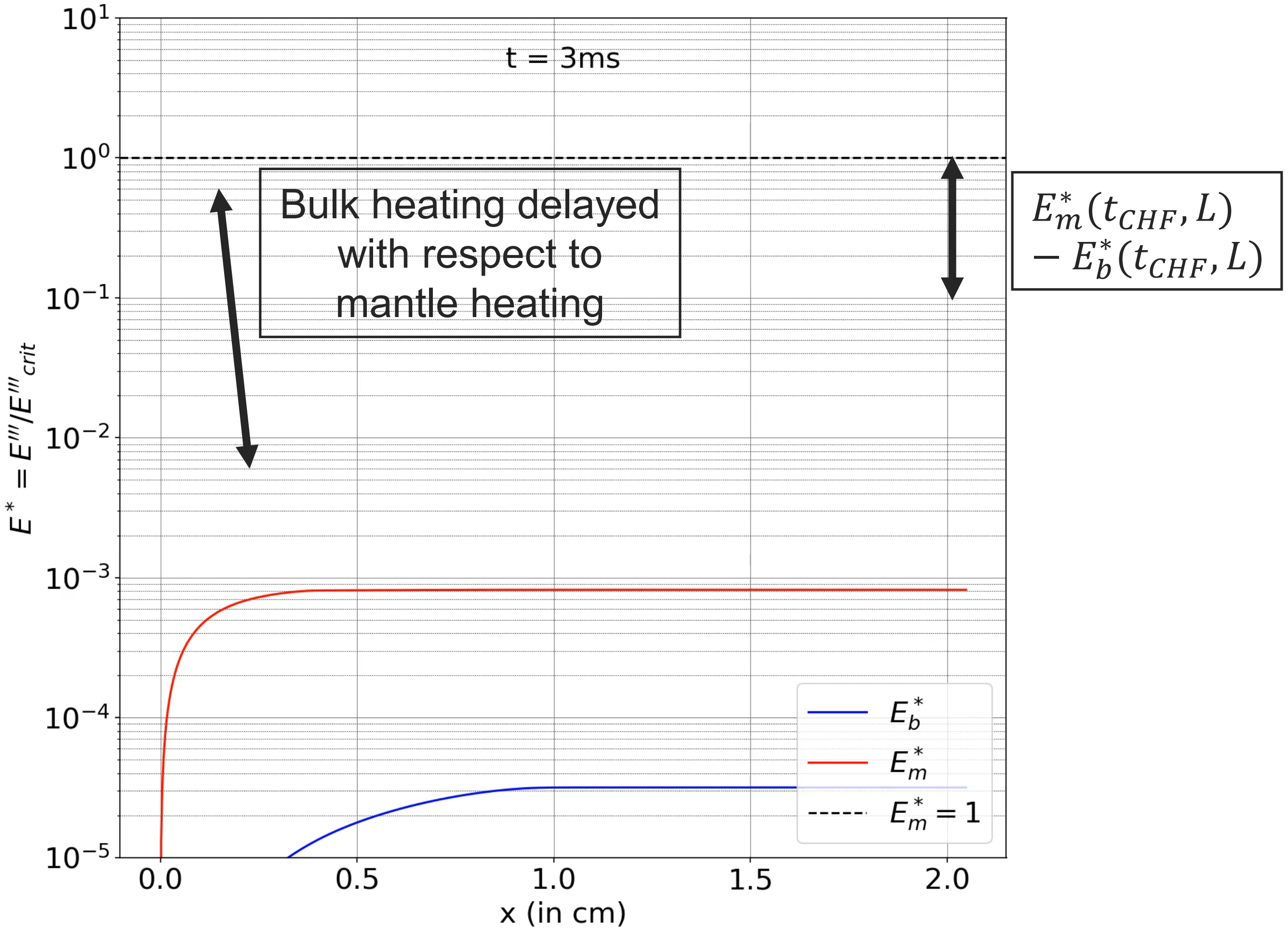
	Simulated conditions
$P\ (bar)$	10
$\Delta T_{sub}(K)$	100
$G\ (10^3 kg.m^{-2}.s^{-1})$	2.6
$\tau\ (ms)$	90
L/e	10

- Non dimensionnal energy:

$$E^* = E'''/E'''_{crit}$$

- Non dimensional boiling criterion

$$E^*_m(t = t_{CHF}, x = L) = 1$$



Bulk heating delayed with respect to mantle heating

$$E^*_m(t_{CHF}, L) - E^*_b(t_{CHF}, L)$$

Homogeneous mantle thickness δ predicted behavior

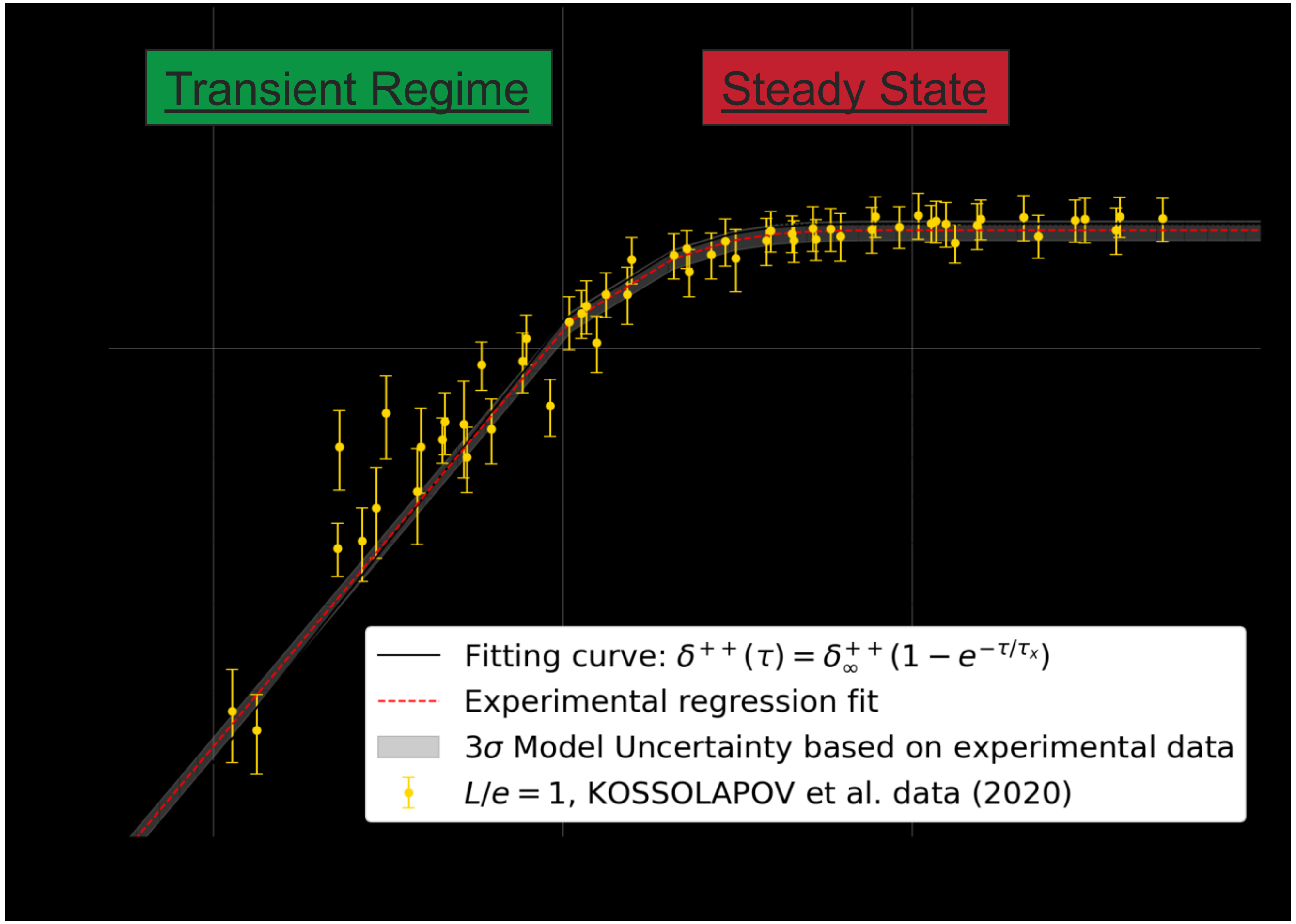
- Characteristic thermal thickness:

$$\delta_T = \frac{\delta_v}{Pr} = \frac{\alpha}{u^*}$$

- Characteristic advection time in the mantle

$$\tau_x = \frac{L}{u_{m\,\infty}}$$

For low aspect ratio data, we have a simple equation to determine δ.



N.B. *The mantle thickness δ is not the thermal boundary layer*

Homogeneous mantle thickness δ predicted behavior

- Characteristic thermal thickness:

$$\delta_T = \frac{\delta_v}{Pr} = \frac{\alpha}{u^*}$$

- Characteristic advection time in the mantle

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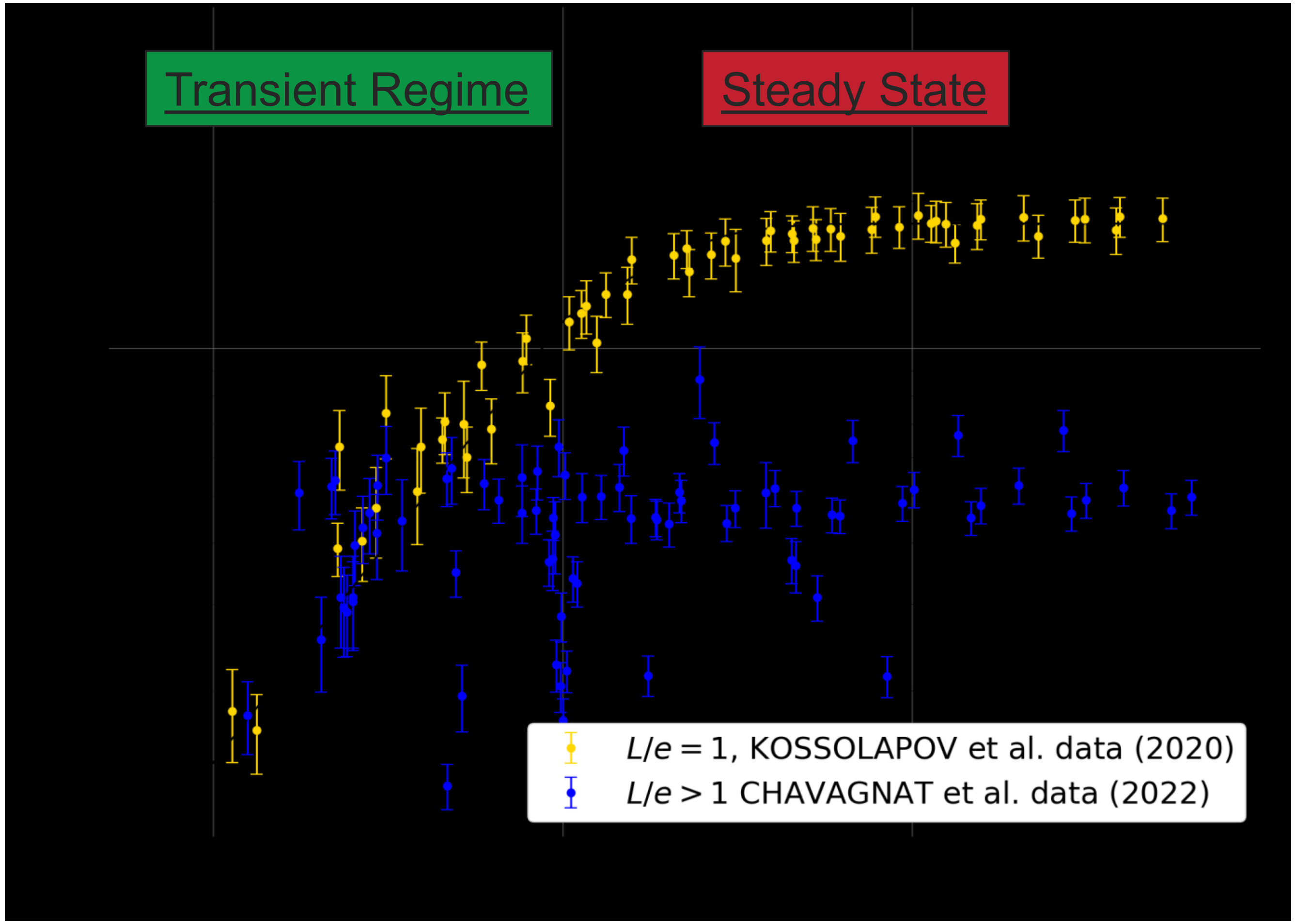
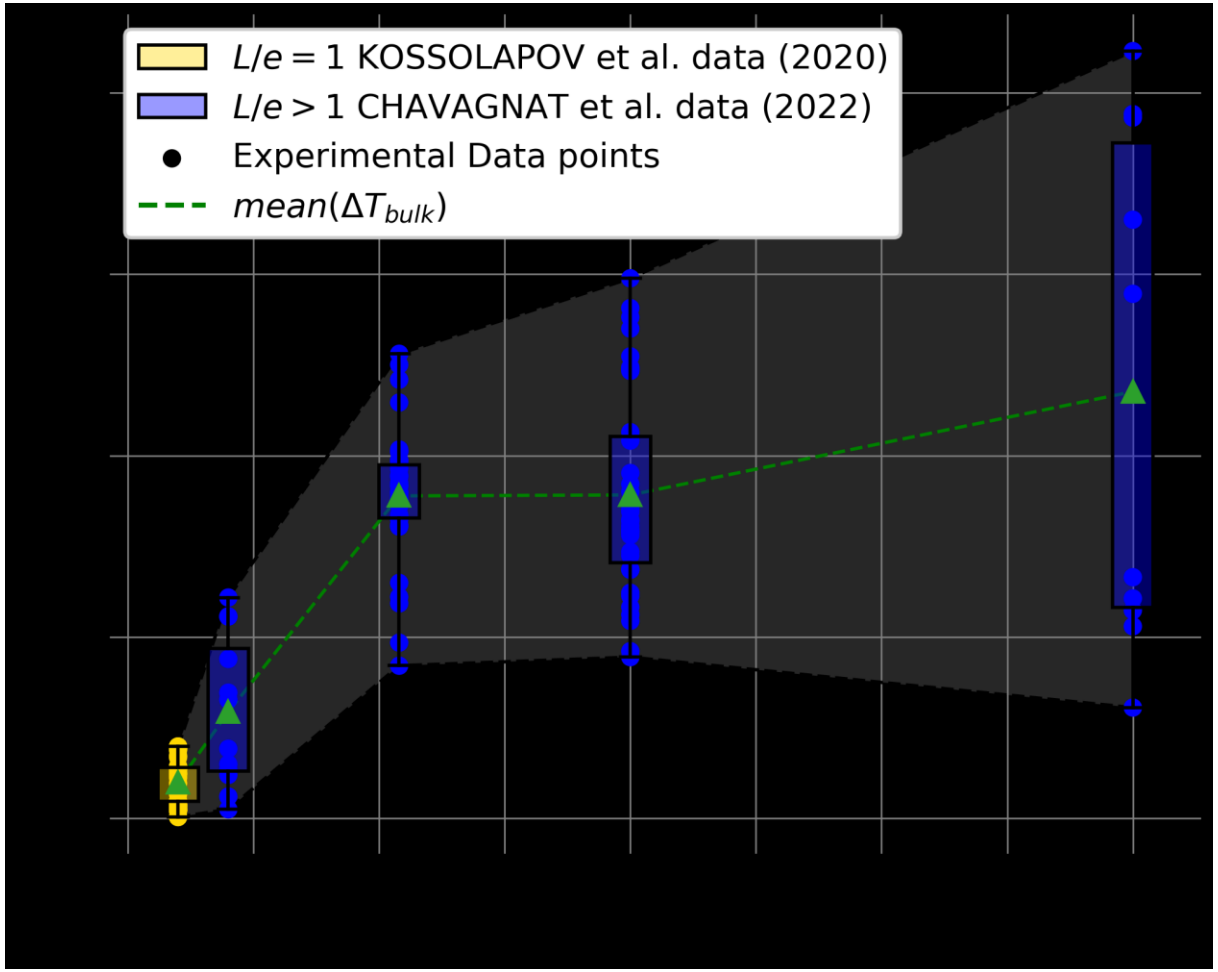


No simple fit on **Chavagnat et al.** data
What is the effect of L/e?

N.B. *The mantle thickness δ is not the thermal boundary layer*

Effect of the aspect ratio on bulk heating



Boxplot showing $\Delta T_{bulk}(L/e)$ computed for all data investigated

- $L/e = 1 \Rightarrow \Delta T_{bulk} \approx 0$

⇒ **Isothermal bulk assumption valid**:

$$\frac{\partial E_m'''}{\partial t} + u_m \frac{\partial E_m'''}{\partial x} + \frac{v_m}{\delta} E_m''' = \frac{q_w''}{\delta}$$

Original model **Nop et al. IJTS 2021**:

- $L/e > 1 \Rightarrow \Delta T_{bulk} \nearrow$

⇒ **Variable bulk temperature mandatory**:

$$\begin{cases} \dfrac{\partial E_m'''}{\partial t} + u_m \dfrac{\partial E_m'''}{\partial x} + \dfrac{v_m}{\delta}\left(E_m''' - E_b'''\right) = \dfrac{q_w''}{\delta} \\ \dfrac{\partial E_b'''}{\partial t} + u_b \dfrac{\partial E_b'''}{\partial x} + \dfrac{v_m}{e-\delta}\left(E_b''' - E_m'''\right) = 0 \end{cases}$$

Extended Model

Consequences of bulk heating on boiling crisis

Assumptions:

- δ known (here computed with the extended model)
- $q''_w(x,t) \propto e^{t/\tau}$

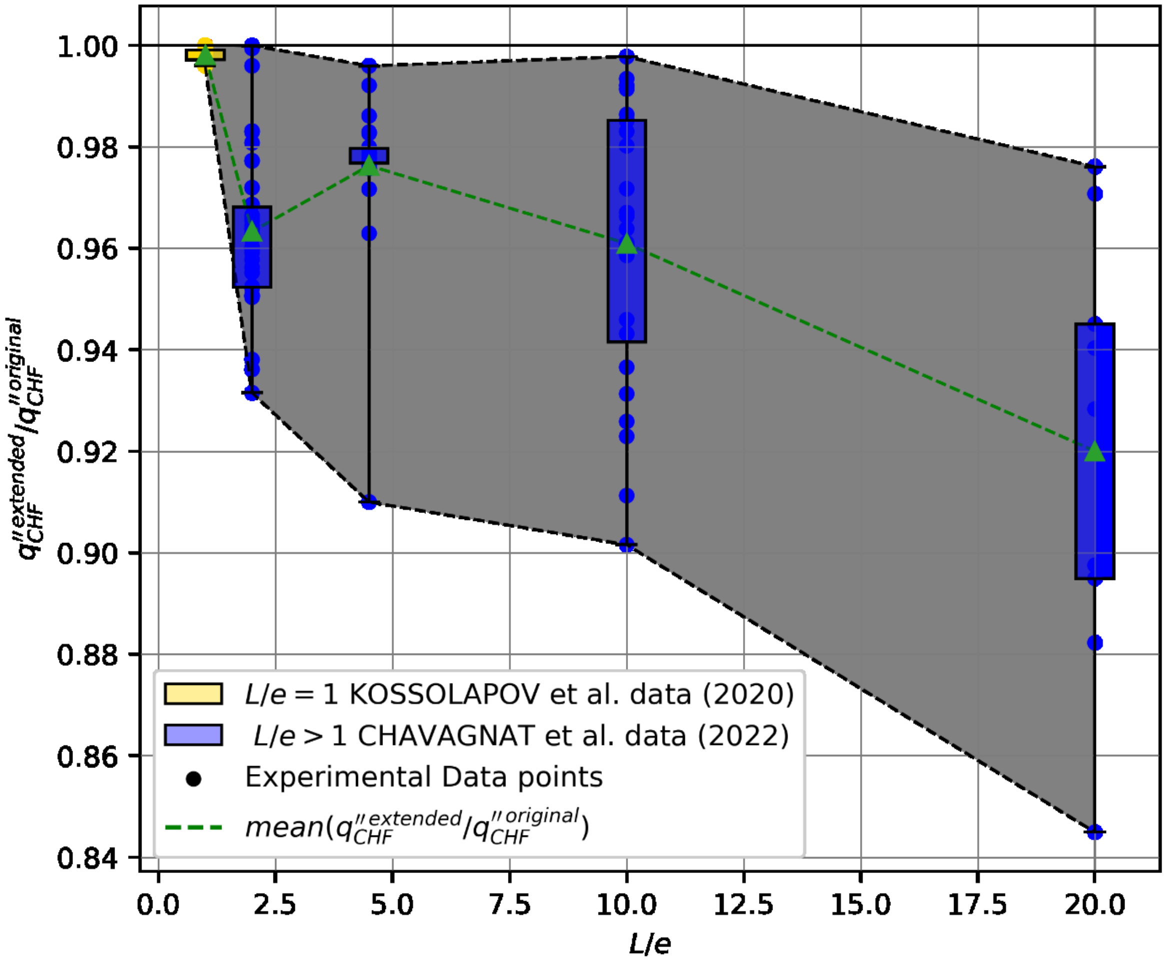
⇒ Analytic expression for the transient CHF

Original model **Nop et al. IJTS 2021**:

$$q''^{\,model}_{CHF}(P, L, \tau, \Delta T_{sub}, G, \delta)$$

Extended model:

$$q''^{\,model}_{CHF}(P, L, e, \tau, \Delta T_{sub}, G, \delta)$$



Bulk heating reduces the efficiency of heat exchanges → premature triggering of the boiling crisis for high L/e

4. Conclusions and perspectives

Presentation key points

In these conditions, knowing δ ⇒ knowing transient CHF

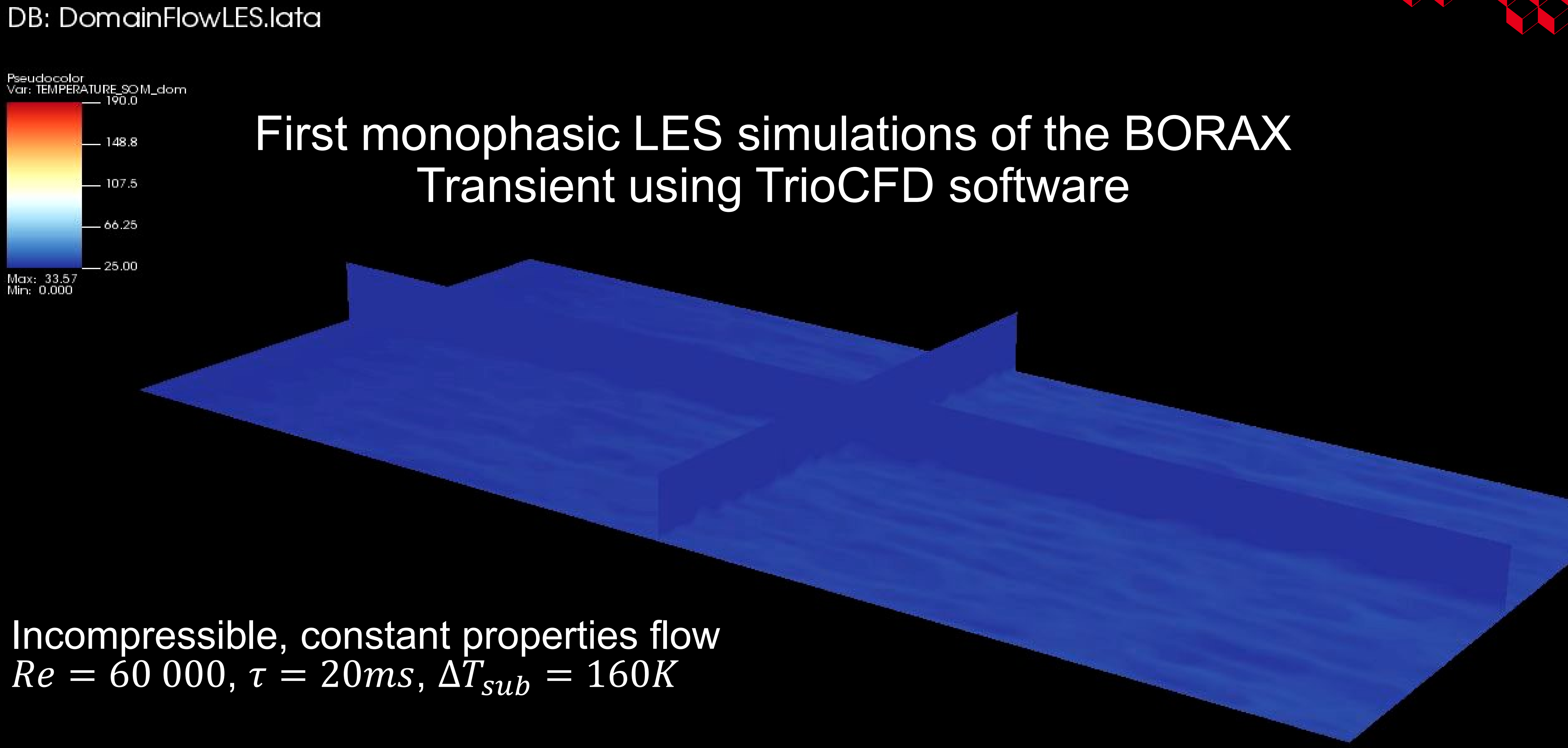
- $\boldsymbol{L/e = 1}$, $T_{bulk} \approx const$, original model assumption **valid**
- $\boldsymbol{L/e > 1}$, $T_{bulk} \nearrow \Rightarrow q''^{\,model}_{CHF} \searrow$, extended model **mandatory**

Upcoming work

Towards reactor geometries ($L \approx 50\text{cm}$, $\mathrm{L/e} \approx 250$) by improving the model's physics

- Solving turbulent temperature fluctuations $v'T'$ by coupling momentum and heat equation
- Take into account variation of **fluid properties** and **pressure** along the channel
- **LES** Thermo-hydraulic simulation using CEA opensource software **TrioCFD**

First monophasic LES simulations of the BORAX Transient using TrioCFD software

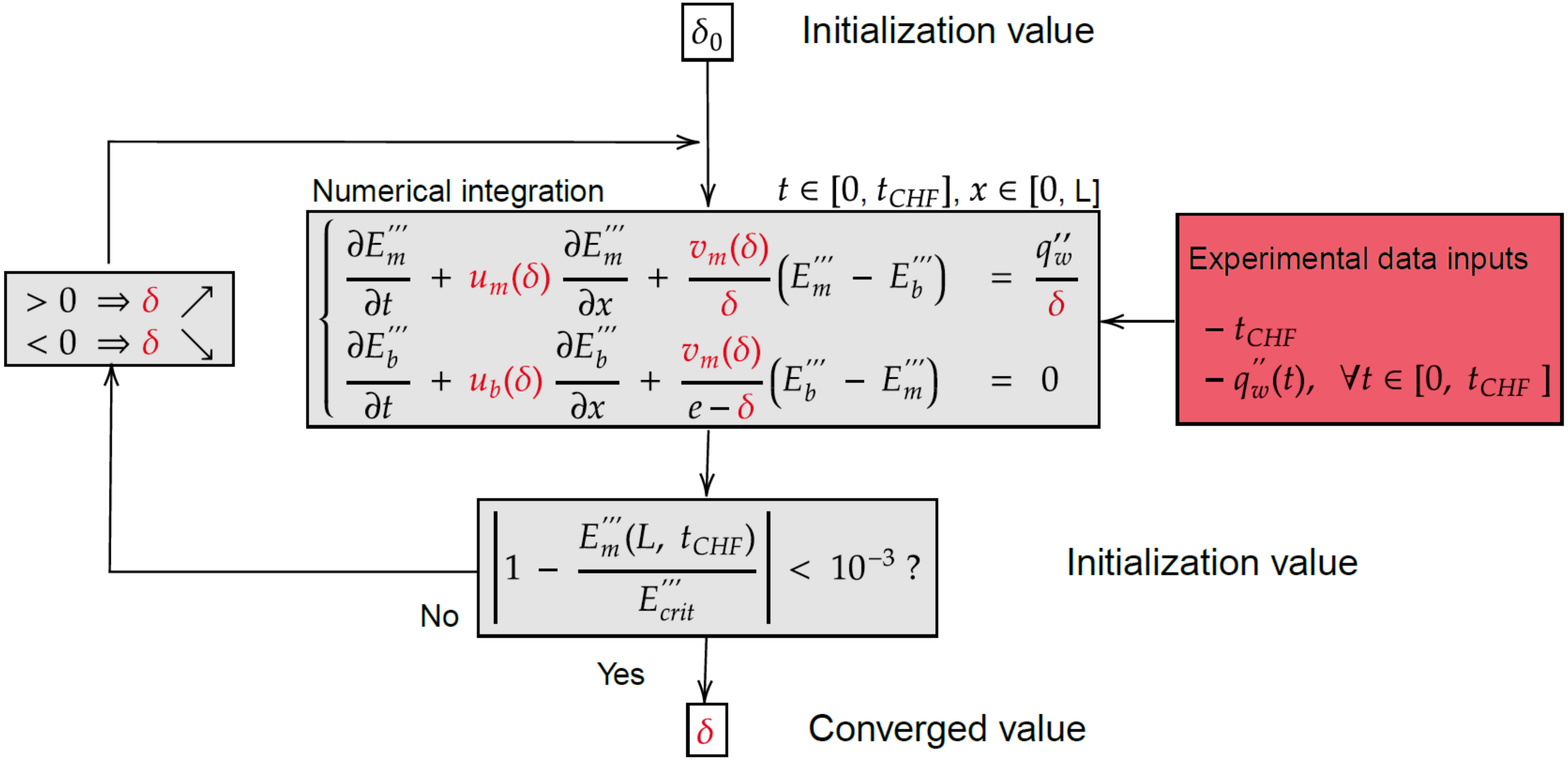


Incompressible, constant properties flow

$Re = 60\ 000,\ \tau = 20ms,\ \Delta T_{sub} = 160K$

5. Addendum

Inverse method to estimate the heated mantle thickness δ



$\boxed{\delta_0}$ Initialization value

Numerical integration $t \in [0, t_{CHF}], x \in [0, \mathrm{L}]$

$$\begin{cases} \frac{\partial E'''_m}{\partial t} + u_m(\delta)\frac{\partial E'''_m}{\partial x} + \frac{v_m(\delta)}{\delta}\left(E'''_m - E'''_b\right) = \frac{q''_w}{\delta} \\ \frac{\partial E'''_b}{\partial t} + u_b(\delta)\frac{\partial E'''_b}{\partial x} + \frac{v_m(\delta)}{e-\delta}\left(E'''_b - E'''_m\right) = 0 \end{cases}$$

Experimental data inputs

- t_{CHF}
- $q''_w(t), \ \forall t \in [0, \ t_{CHF}\ ]$

$$> 0 \Rightarrow \delta \nearrow$$
$$< 0 \Rightarrow \delta \searrow$$

$$\left| 1 - \frac{E'''_m(L, \ t_{CHF})}{E'''_{crit}} \right| < 10^{-3} \ ?$$

Initialization value

No

Yes

$\boxed{\delta}$ Converged value

N.B. *Numerical integration performed by explicit finite differences*

Heat transport by the flow velocity fluctuations at the mantle-bulk interface

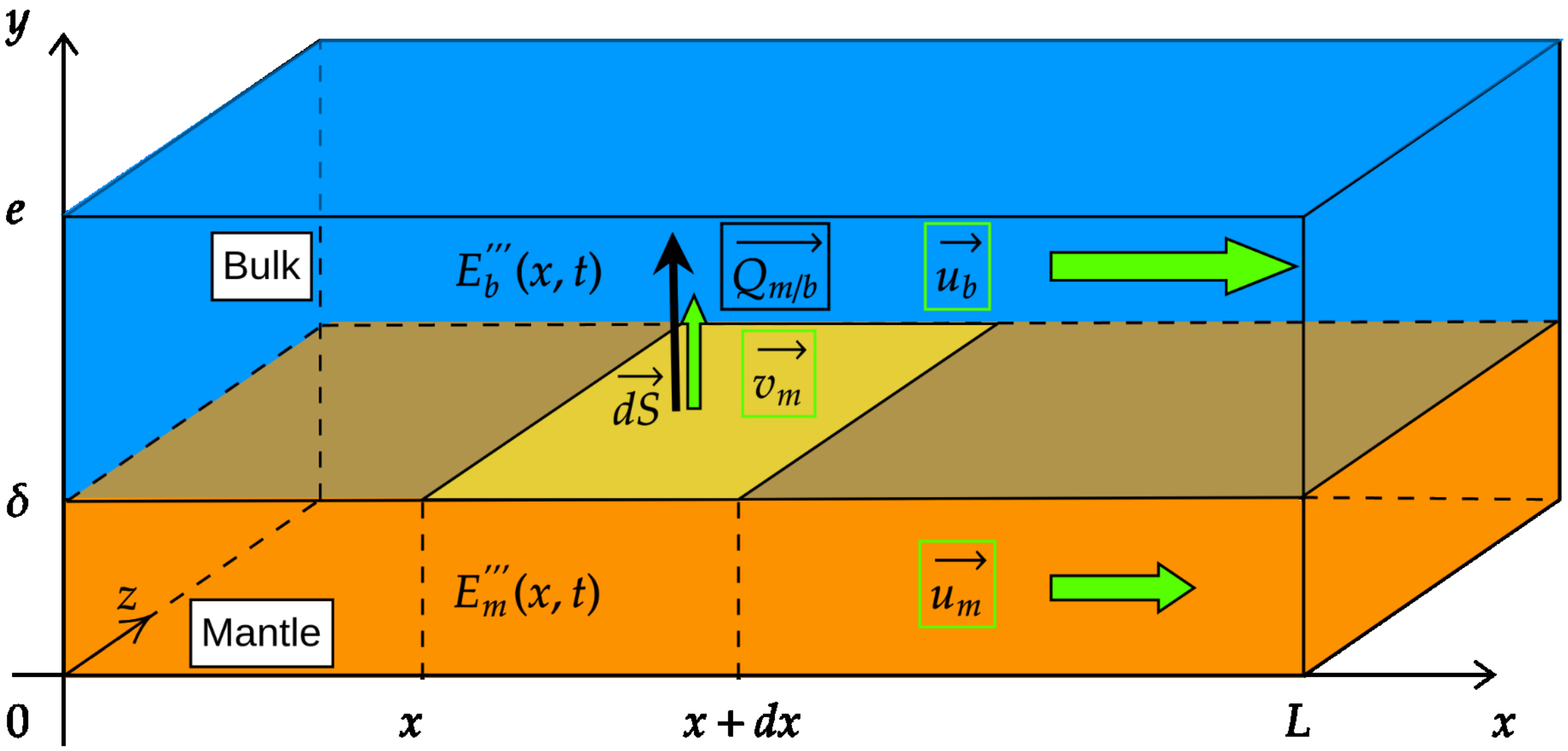
Heat flux transported at the interface

$$\overrightarrow{Q_{m/b}} = v_m\left(E_m'''(x,t) - E_b'''(x,t)\right)\overrightarrow{dS}$$

Characteristic transverse fluctuation velocity:

$$v_m = \int_0^{+\infty} v' P(v') dv'$$

v' is extracted from isothermal DNS flow data from **Moser et Al. (PoF) 1999** and **Graham et Al (JoT) 2016**



Computation of the transverse turbulent characteristic velocity $\overrightarrow{v_m}$

Heat flux transported at the interface:

$$\overrightarrow{Q_{m/b}} = v_m\left(E_m'''(x,t) - E_b'''(x,t)\right)\overrightarrow{dS}$$

Characteristic transverse fluctuation velocity:

$$v_m = \int_0^{+\infty} v'P(v')dv'$$

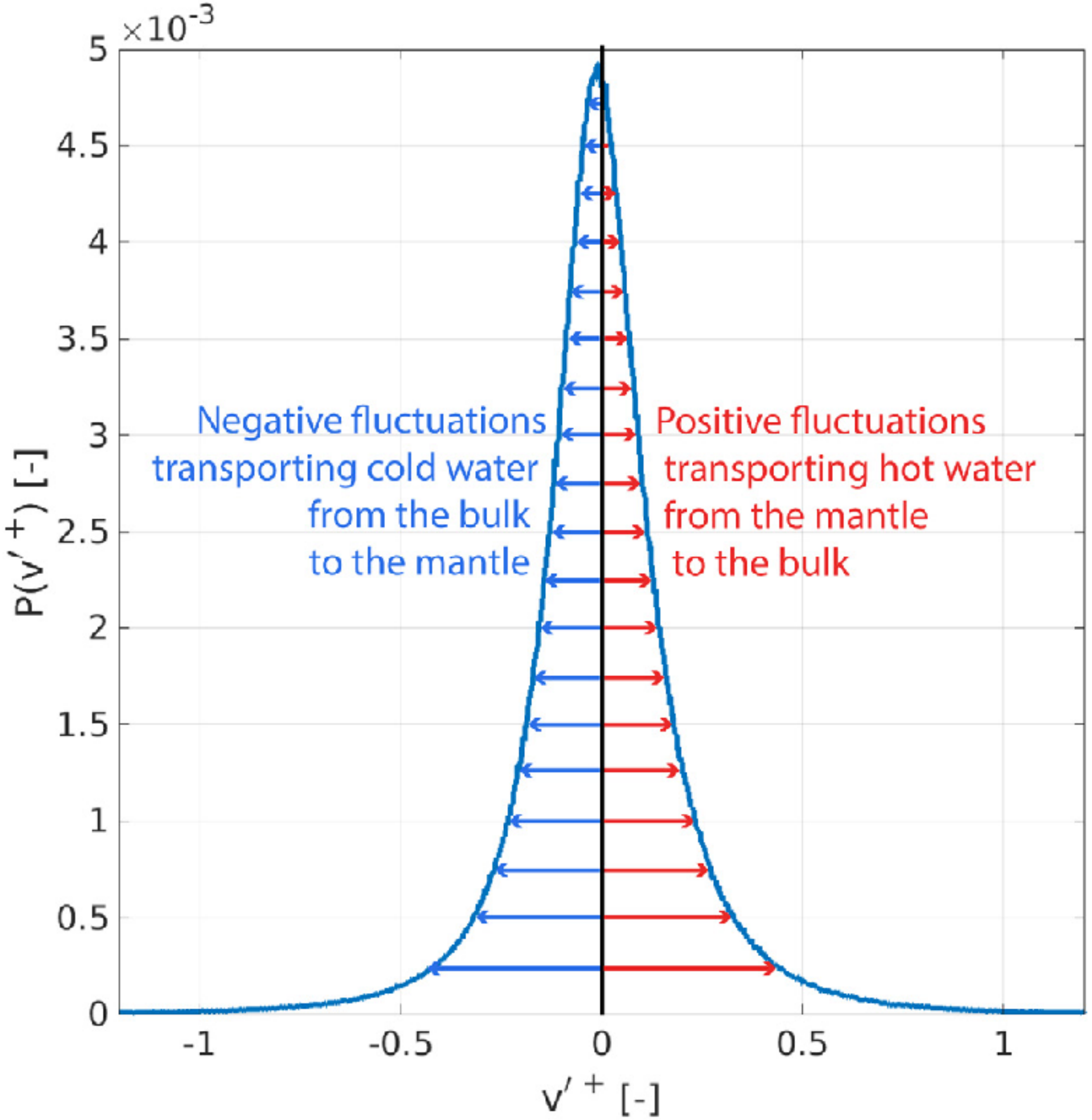


Figure 8: *PDF of the velocity fluctuations contributions at the interface. Computed using DNS data from Moser et Al. (1999) [PoF] and Graham et Al (2016)[JoT]*