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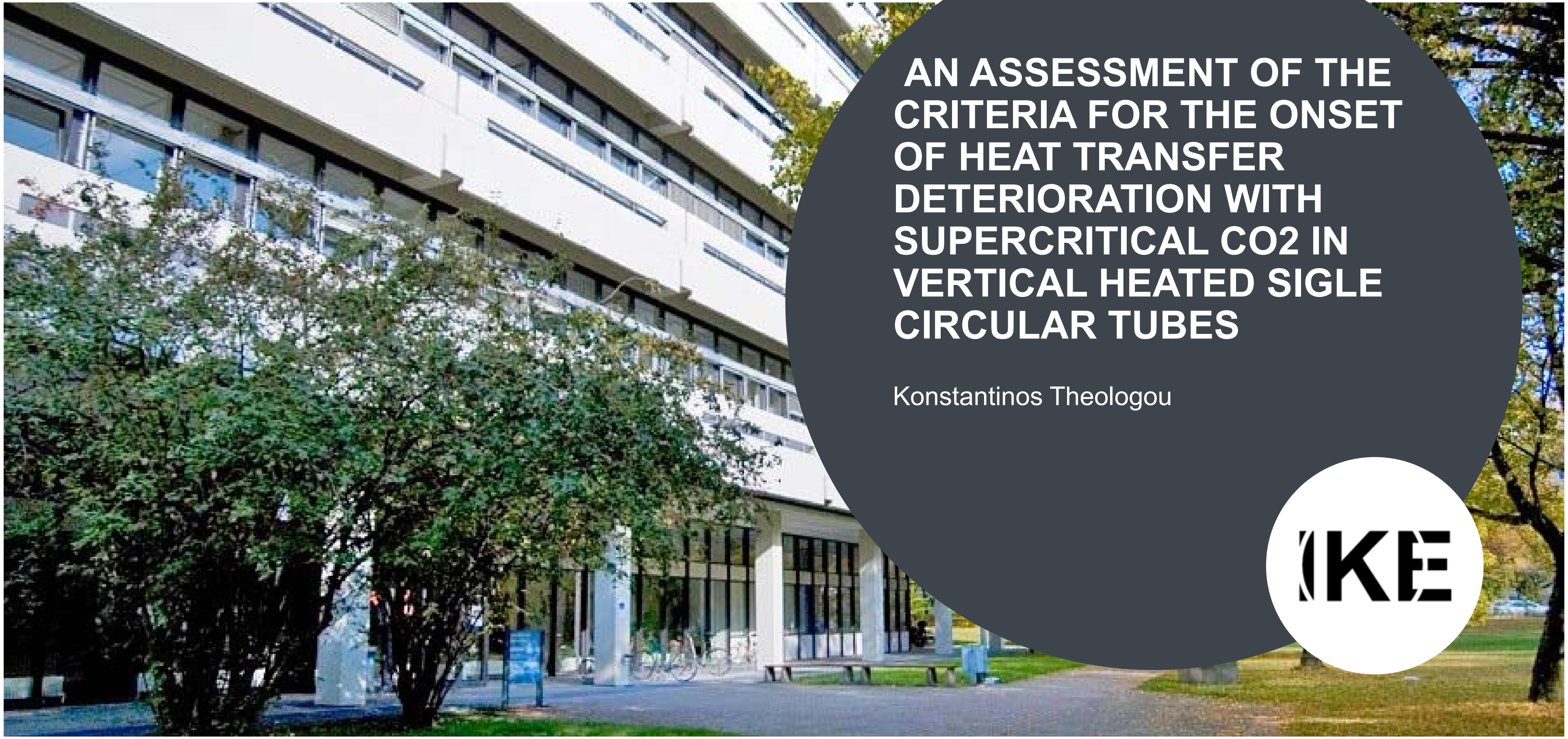

AN ASSESSMENT OF THE CRITERIA FOR THE ONSET OF HEAT TRANSFER DETERIORATION WITH SUPERCRITICAL CO2 IN VERTICAL HEATED SIGLE CIRCULAR TUBES

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Outline

- Motivation and aims
- Experimental setup
- Data reduction
- Results
- Summery & Conclusion

Motivation

since Fukushima the decay heat removal became a main part in the reactor safety research

STARTING POSITION

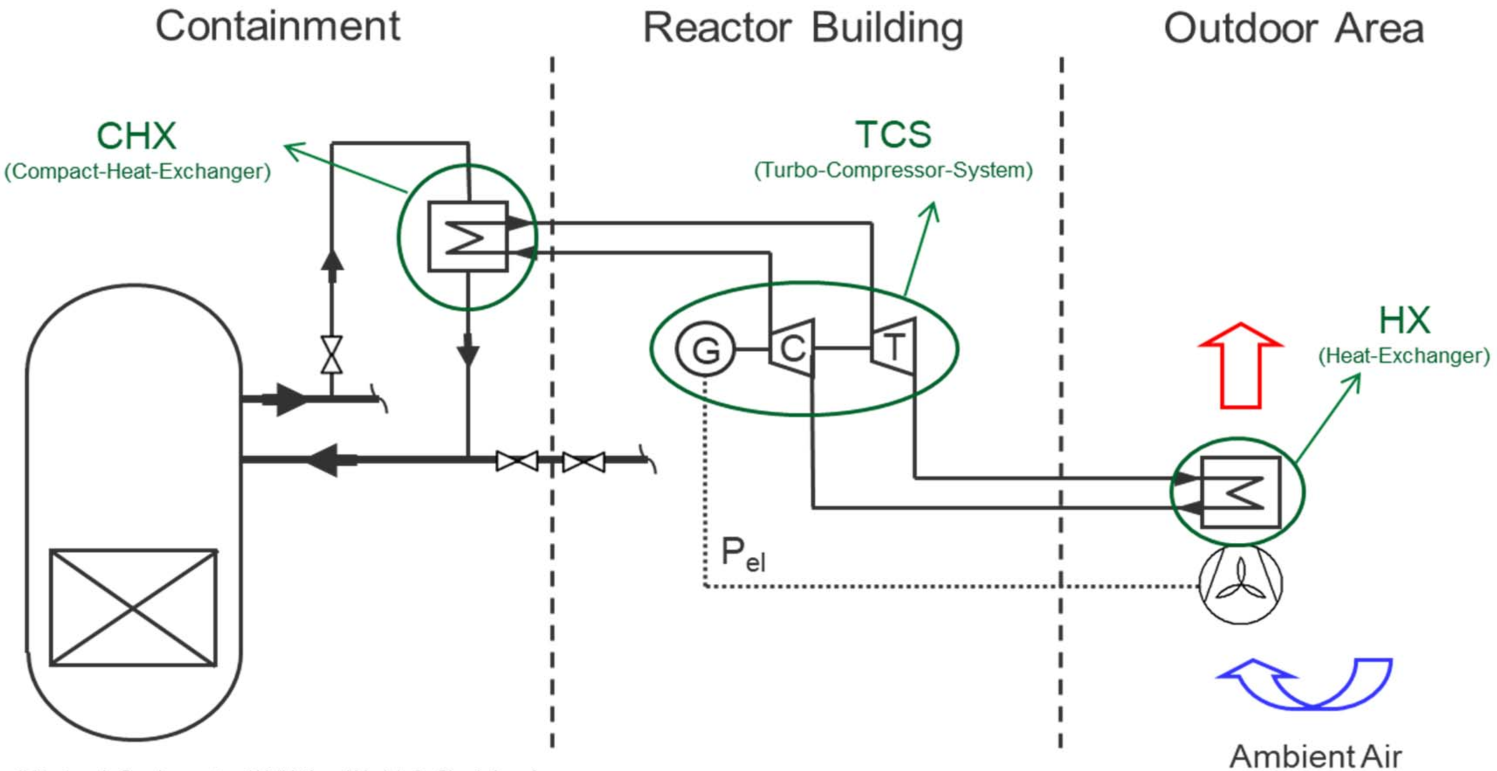
- decay heat must be transferred from the reactor core to the environment
- possibility that active safety system does not work
- passive safety systems and redundant heat sinks of new reactor concepts can not be retrofitted into existing plants

NEW CONCEPT

- sCO_2-operated decay heat removal system based on a Brayton cycle
- works without power grid connection, is self-sufficient and starts automatically
- compact system, can be retrofitted into existing power plants

Motivation

new concept - sCO_2-operated decay heat removal system



1) Venker, J.: Development and Validation of Models for Simulation of Supercritical Carbon Dioxid Brayton Cycles and Application to Self-Propelling Heat Removal Systems in BWR. Dissertation, 2015

Aims

before implementing such a system accurate system simulations are needed

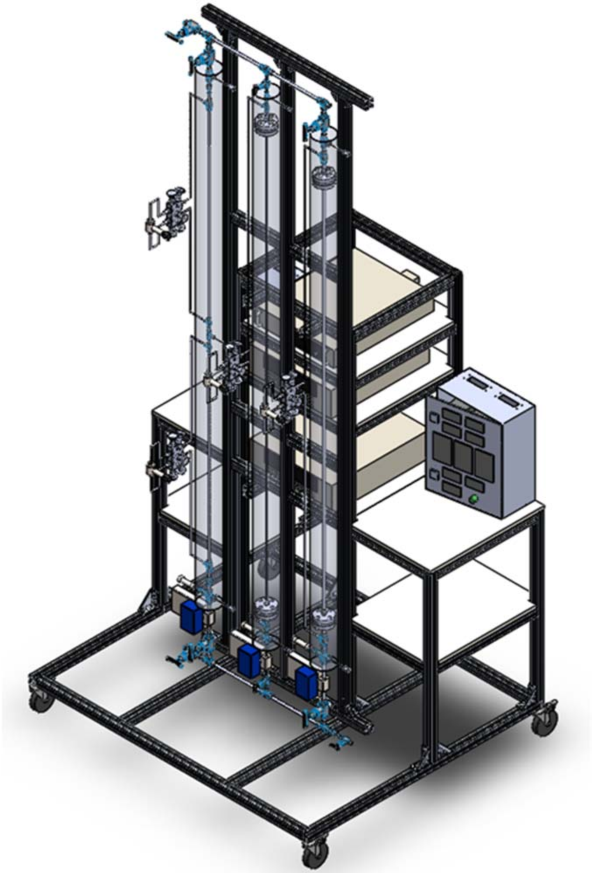
- the system was simulated with the German thermal hydraulic system code ATHLET by Venker but the results of the simulation show large deviations to the existing experimental data near the critical point
- ATHLET uses heat transfer and pressure loss correlations, so experimental data is needed to validate these correlations

In this presentation:

→ investigation of heat transfer characteristics for heated single circular tubes for an upward flow and determine criteria for the onset of heat transfer deterioration

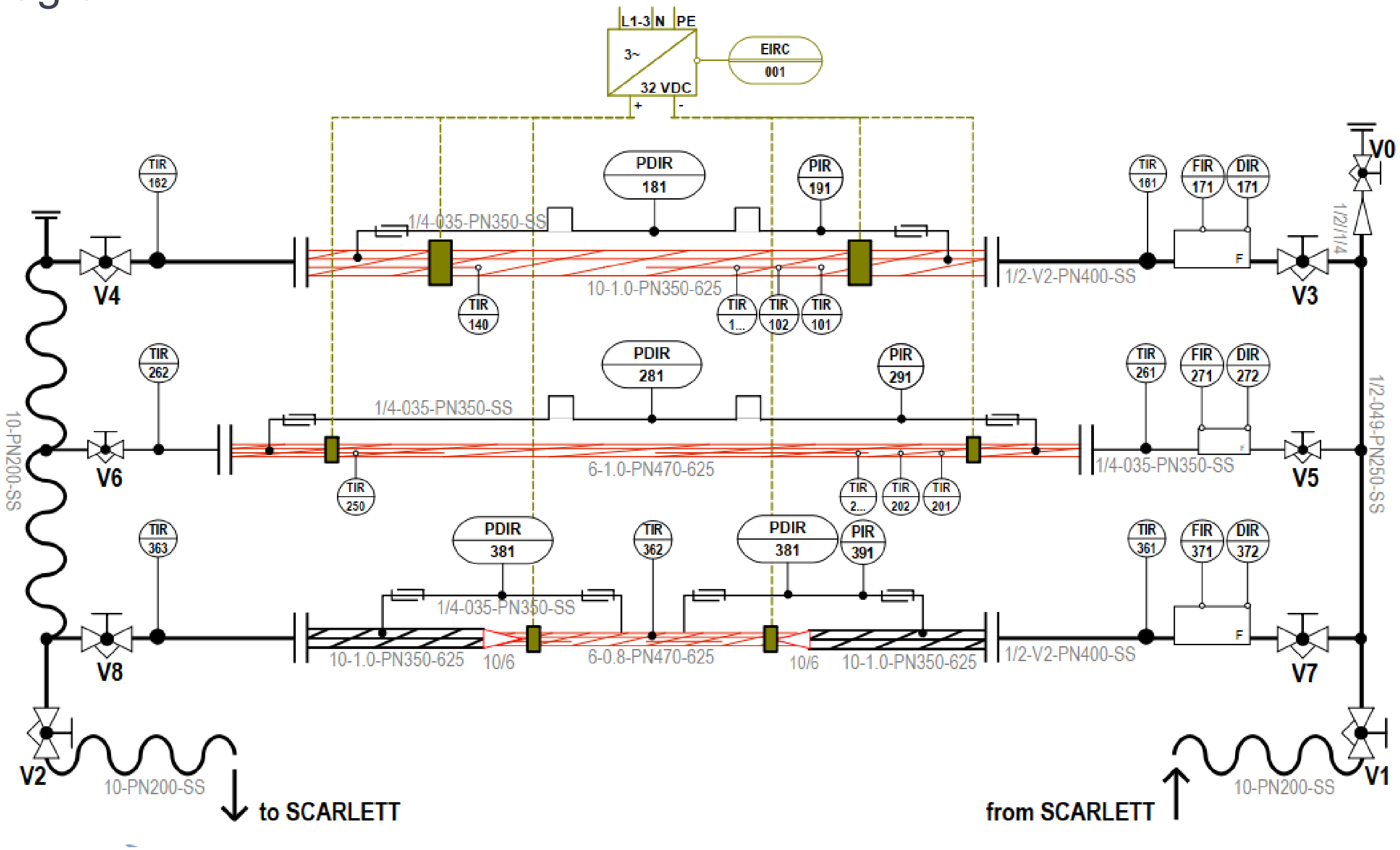
Experimental Setup

overview



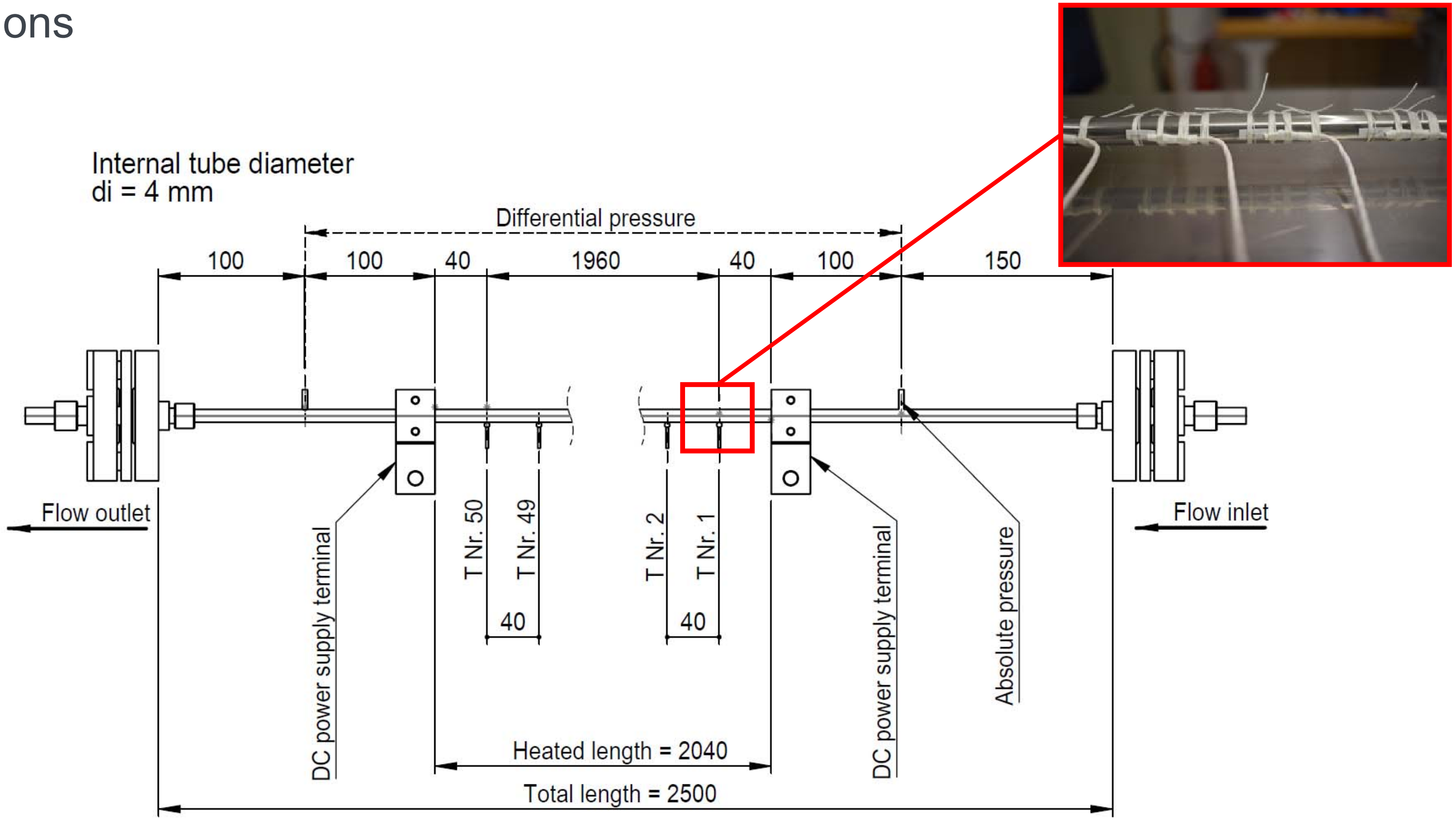
Experimental Setup

P&I diagram



Experimental Setup

dimensions



Experimental Setup

instrumentation

Device	Manufacturer	Specification	Parameter	Accuracy
DC power supply	Magna-Power	XR32-310/380	current, voltage	± 0,075 % FS (prog.) ± 0,2 % FS (mon.)
differential pressure transmitter	Keller	PD-33X	differential pressure	± 0,15 % FS
absolute pressure transmitter	Keller	PA-33X	absolute pressure	± 0,15 % FS
coat resistance temperature sensor	Electronic Sensor	PT100	flow temperature	± 0,15+0,002*T RD
surface thin-film resistance temperature sensor	Electronic Sensor	PT100 (3,0x0,8x1,0)	pipe surface temperature	± 0,15+0,002*T RD
Coriolis mass flow meter	Schwing	RHM04L RHM03L +RHE26	mass flow	± 0,17 % FS
Coriolis mass flow meter	Schwing	RHM04L RHM03L +RHE26	density	± 2,0 % FS. (± 2 kg/m^3)

Data reduction

measured parameter

$$\dot{m};\ T_{b,in};\ T_{b,out}; T_{sur,x}; p_{in};\ p_{diff}; I; V$$

1. Calculation of heat flow

$$\left|\dot{Q}_1\right| = \left|\dot{Q}_2\right| = \dot{Q}\ \ [\mathrm{W}]$$

$$\dot{Q}_1 = \dot{m}_1 * [h_1''(\vartheta'', p'') - h_1'(\vartheta', p')]\ \ \ [\mathrm{W}]$$

2. Calculation of heat flux

$$\dot{Q}_2 = P_{el} = U * I\ \ [\mathrm{W}]$$

$$\dot{q}_{tube} = \frac{\dot{Q}_2}{A_{i,sur}} = \frac{U*I}{\pi*d_i*L_h}\ \ \left[\frac{\mathrm{W}}{\mathrm{m}^2}\right]$$

3. Calculation of the bulk enthalpy

$$i_{b,x} = i_b' + \left(\frac{L_x}{L_h}\right) * \frac{\dot{Q}_2}{\dot{m}}\ \ \left[\frac{\mathrm{kJ}}{\mathrm{kg}}\right]$$

4. Calculation of bulk fluid temperature

$T_{b,x} = f\left(i_{b,x}, p_x\right)\ [°\mathrm{C}]$ with $p_x = p_{in} - \frac{p_{diff}}{L_h} * L_x\ [\mathrm{bar}]$

5. Calculation of volumetric heat flux

$$\dot{q}_V = \frac{\dot{Q}_2}{\frac{\pi}{4}(d_o^2 - d_i^2) * L_h}\ \left[\frac{\mathrm{W}}{\mathrm{m}^3}\right]$$

6. Calculation of inner wall temperature

$$T_{W,i} = T_{W,o} + \frac{q_V}{4\lambda_w}\left[\left(\frac{d_o}{2}\right)^2 - \left(\frac{d_i}{2}\right)^2\right] - \frac{q_V}{2\lambda_w}\left(\frac{d_o}{2}\right)^2 * \ln\left(\frac{d_o}{d_i}\right)\ [°\mathrm{C}]$$

7. Calculation of heat transfer coefficient

$$h_x = \frac{\dot{q}}{T_{W,x} - T_{b,x}}\ \left[\frac{\mathrm{W}}{\mathrm{m}^2\mathrm{K}}\right]$$

Data reduction

criteria for the onset of deteriorated heat transfer (DHT)

- **criterion based on buoyancy (Jackson et al.)**

$$\frac{\overline{\mathrm{Gr}}_\mathrm{b}}{\mathrm{Re}_\mathrm{b}^{2.7}} > 10^{-5}$$

$$\overline{\mathrm{Gr}}_\mathrm{b} = \frac{(\varrho_\mathrm{b} - \bar{\varrho})\mathrm{g}\mathrm{d}_\mathrm{i}^3}{\varrho_\mathrm{b}\nu_\mathrm{b}^2}$$

- **criterion based on buoyancy (McEligot and Jackson)**

$$\mathrm{Bo}^* = \frac{\mathrm{Gr}^*}{\mathrm{Re}_\mathrm{b}^{3.425}\mathrm{Pr}^{0.8}} > \sim 6 * 10^{-7}$$

$$\mathrm{Gr}^* = \frac{\mathrm{g}\beta_\mathrm{b}\dot{\mathrm{q}}\mathrm{d}_\mathrm{i}^4}{\lambda_\mathrm{b}\nu_\mathrm{b}^2}$$

- **criterion based on flow acceleration (Petukhov et al.)**

$$\left(\frac{\xi_u}{\xi}\right)_{max} > 1 - 1.3$$

$$\xi = \left(\frac{\varrho_w}{\varrho_b}\right)^{0.4}\left(1.82 log\left(\frac{Re_b}{8}\right)\right)^2$$

$$\xi_u \cong 8\dot{q}_b^+$$

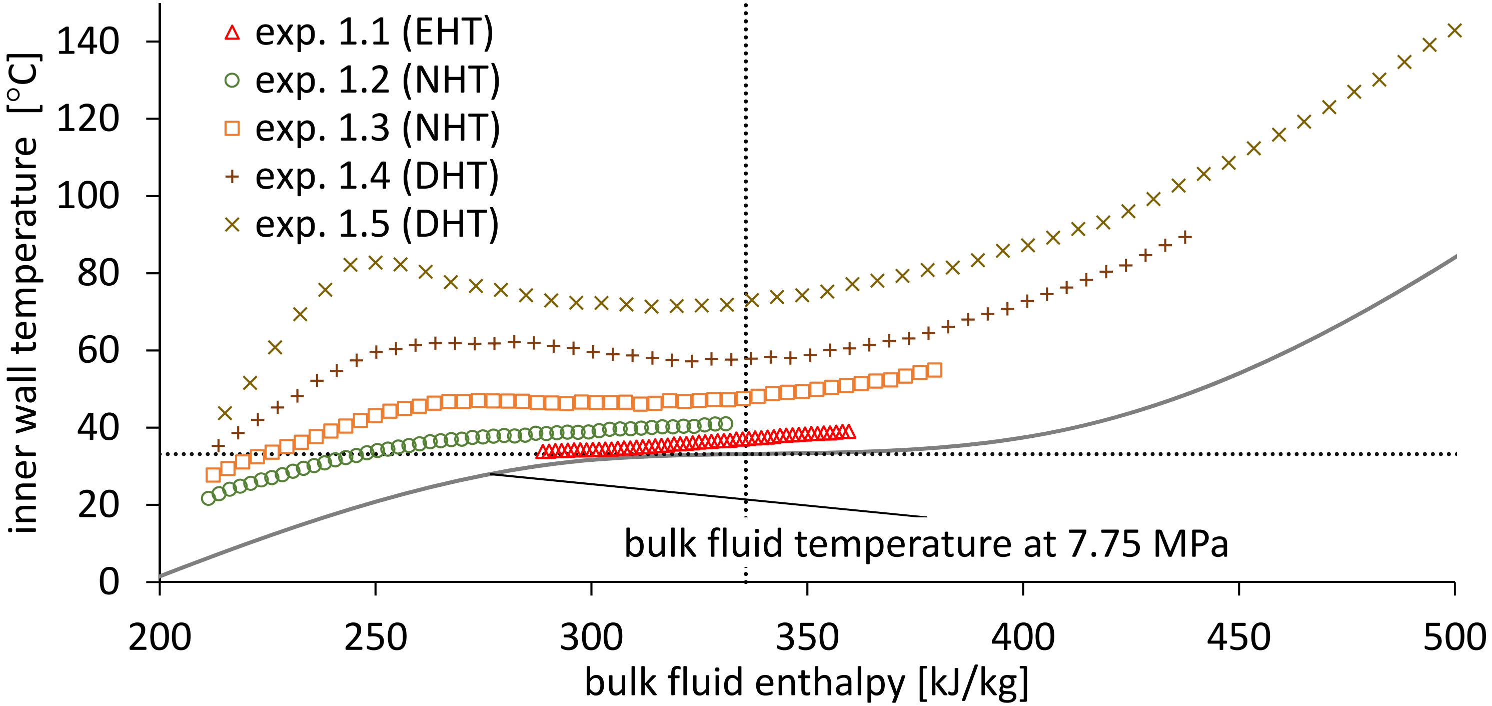
- **criterion based on heat flux to mass flux ratio (Jeon et al.)**

$$\dot{\mathrm{q}} > 0.2\mathrm{G}^2$$

Results

first test series

$$d_i = 4\ mm; G = 800 kg/m^2s;\ \dot{q} = 30, 50, 70, 90, 110\ kW/m^2; p = 7.75\ MPa$$

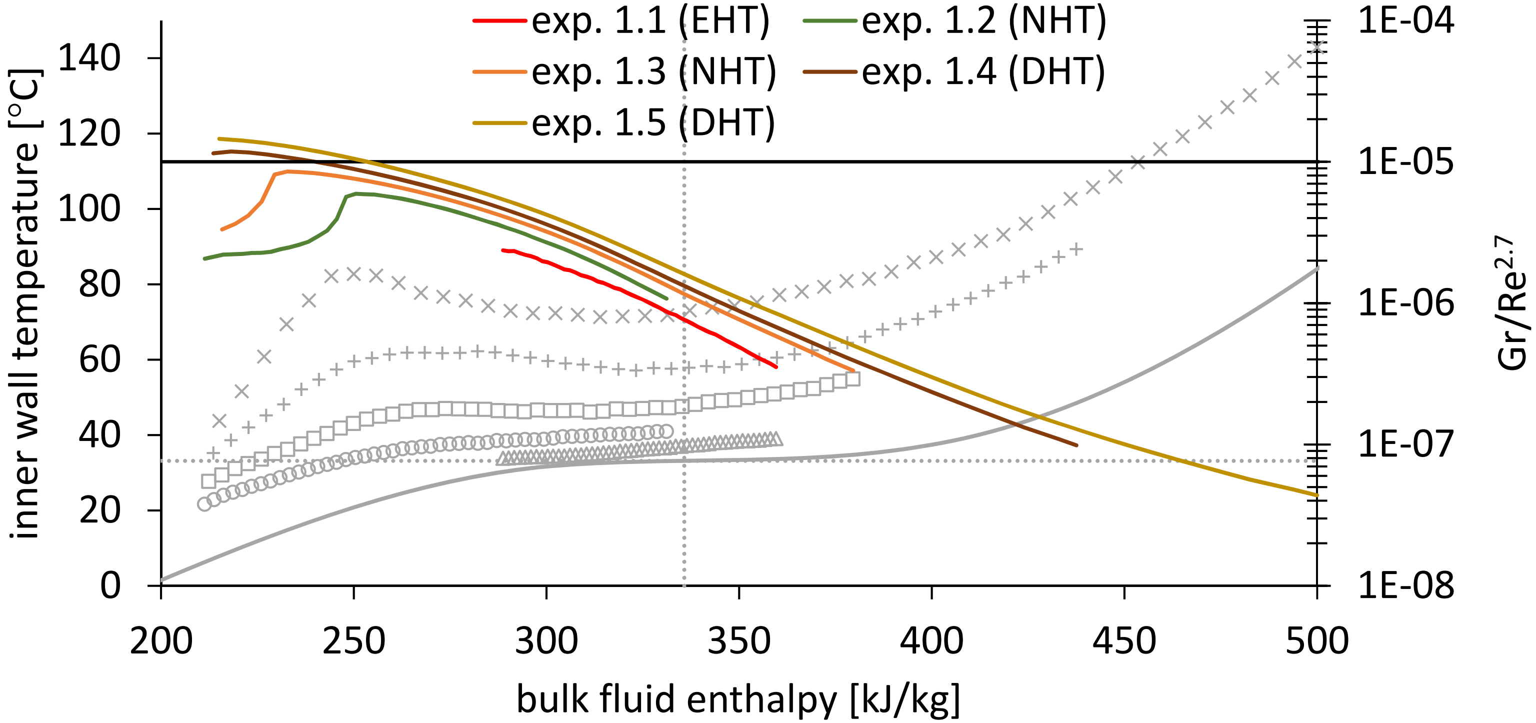


categorization of the heat transfer regime

Results

first test series – criterion based on buoyancy (Jackson et al.)

$$d_i = 4\,mm; G = 800 kg/m^2 s;\ \dot{q} = 30, 50, 70, 90, 110\ kW/m^2; p = 7.75\ MPa$$

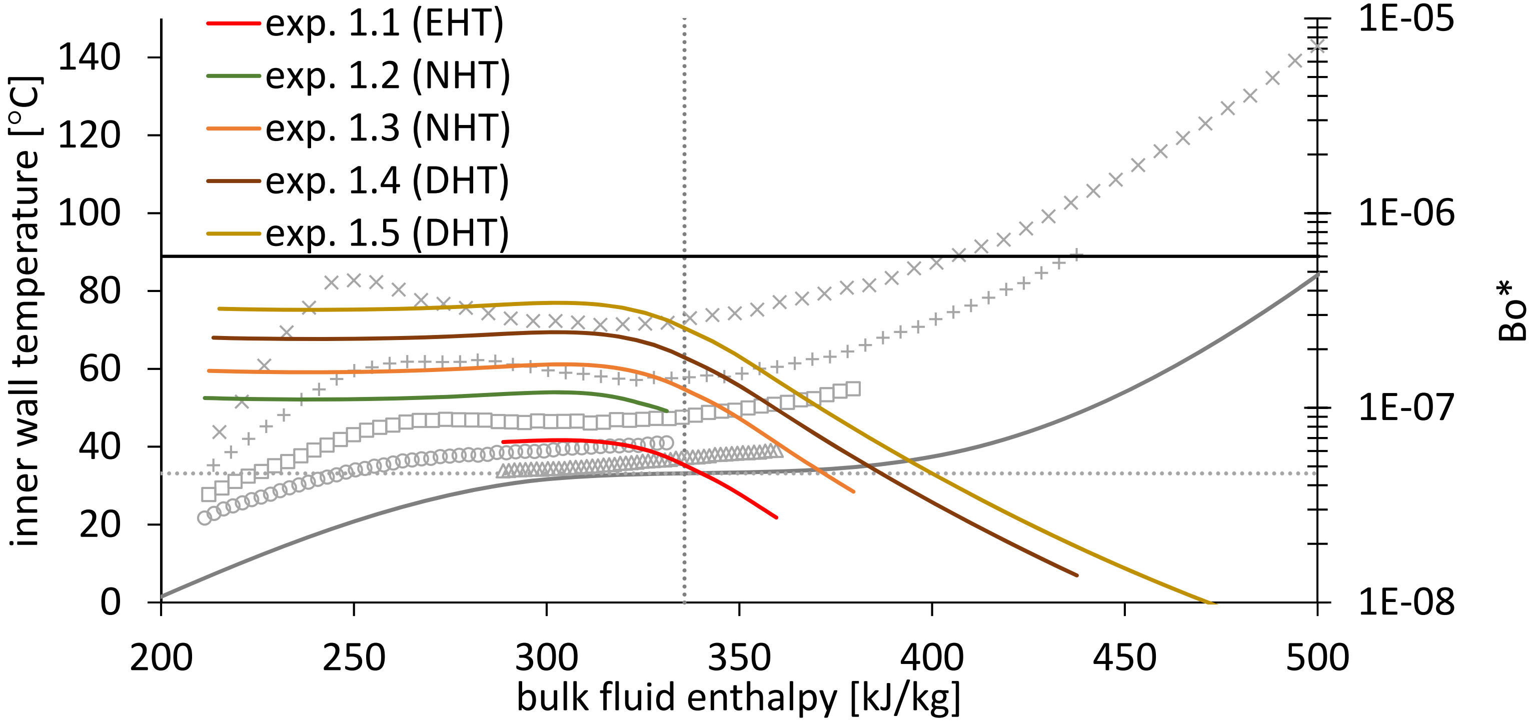


criterion in compliance with 5/5 experiments

Results

first test series – criterion based on buoyancy (McEligot and Jackson)

$d_i = 4\,mm; G = 800 kg/m^2 s;\ \dot{q} = 30, 50, 70, 90, 110\ kW/m^2; p = 7.75\ MPa$

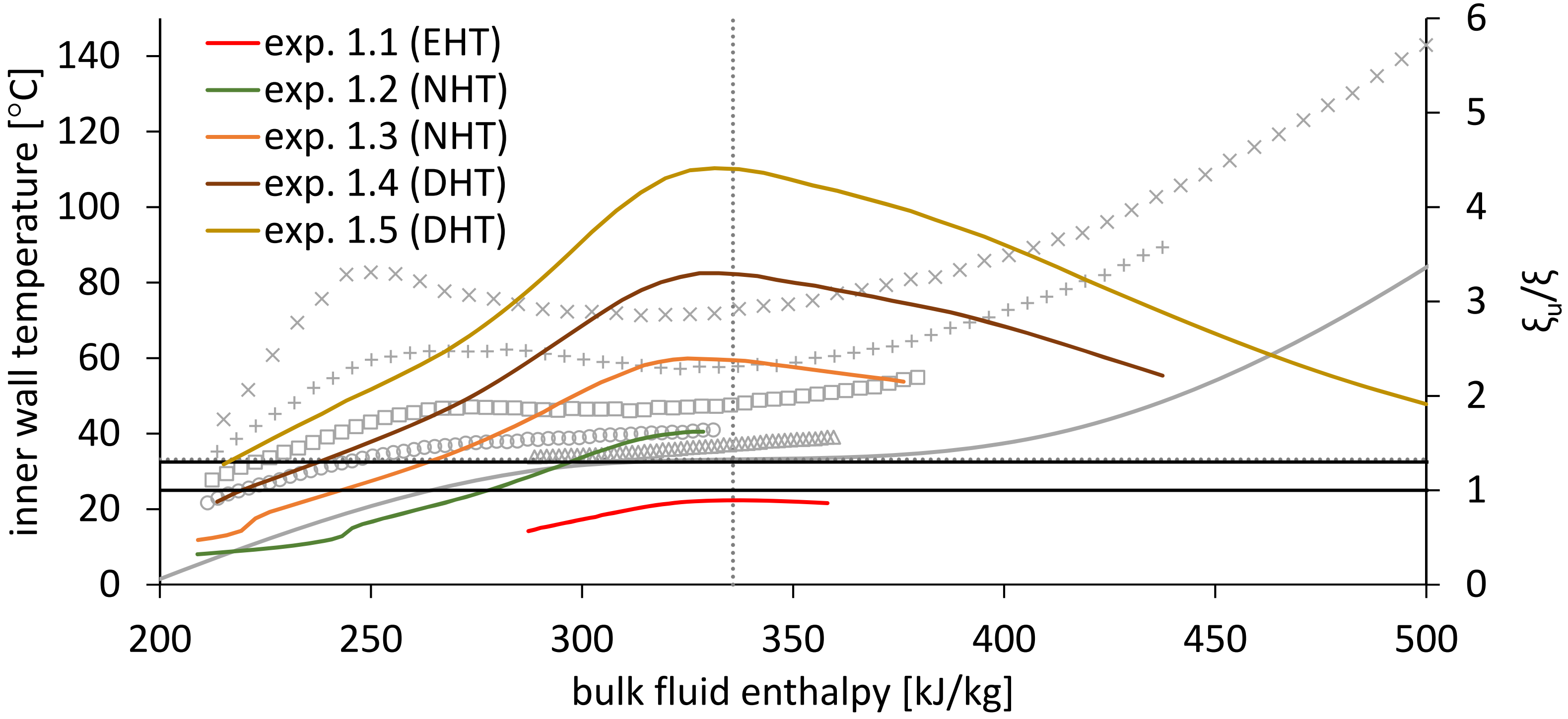


criterion in compliance with 3/5 experiments

Results

first test series – criterion based on flow acceleration (Petukhov et al.)

$$d_i = 4\,mm; G = 800 kg/m^2 s;\ \dot{q} = 30, 50, 70, 90, 110\ kW/m^2; p = 7.75\ MPa$$

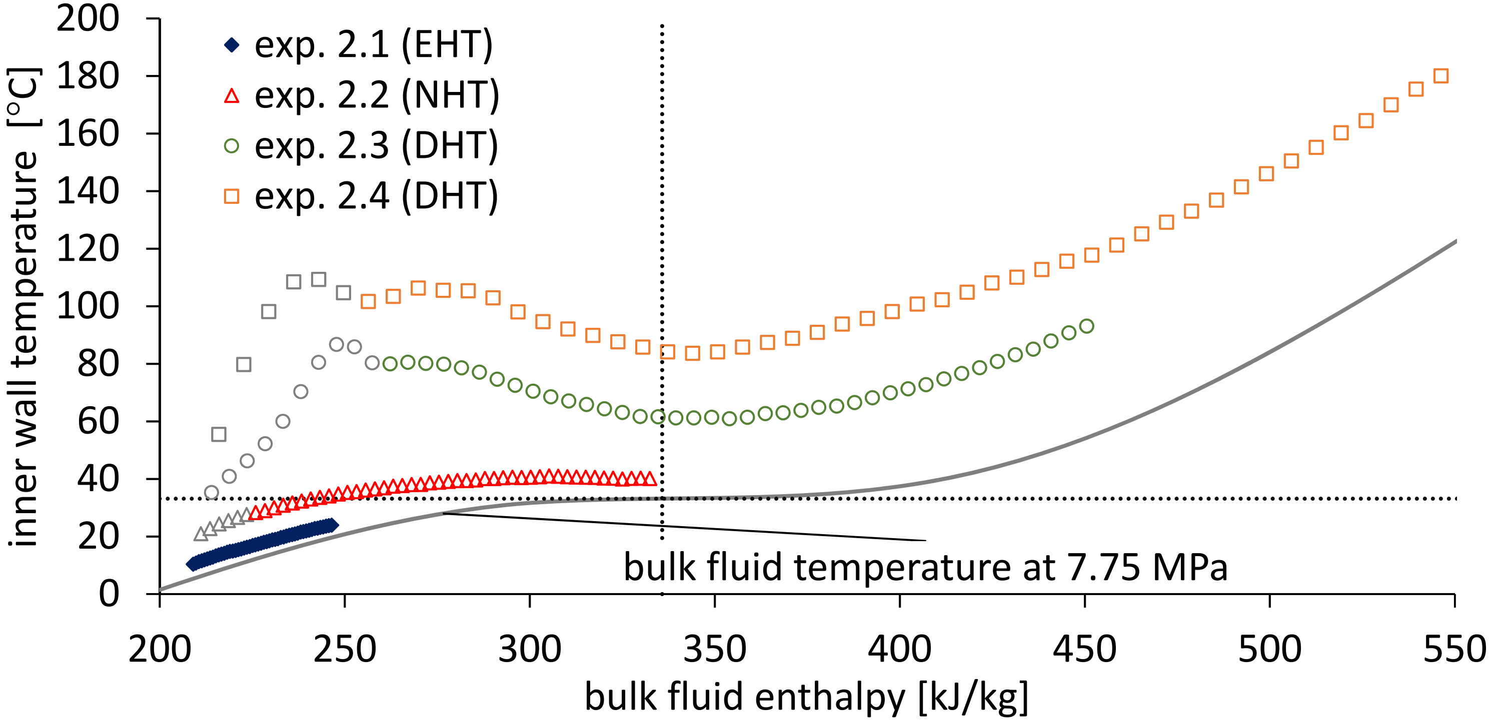


criterion in compliance with 3/5 experiments

Results

second test series

$d_i = 4\,mm;G = 400kg/m^2s;\;\dot{q} = 10,30,50,70\;kW/m^2;p = 7.75\;MPa$

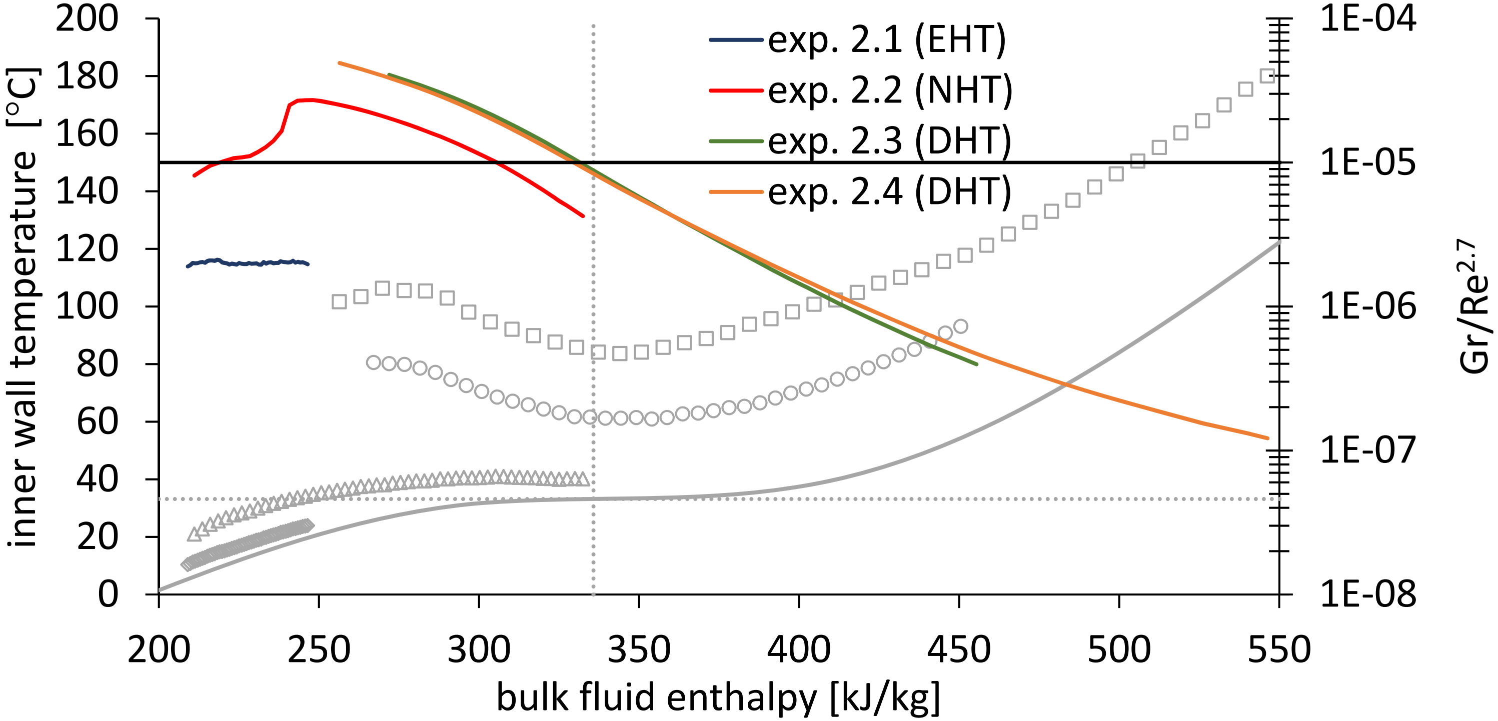


categorization of the heat transfer regime

Results

second test series – criterion based on buoyancy (Jackson et al.)

$$d_i = 4\,mm; G = 400 kg/m^2 s;\ \dot{q} = 10, 30, 50, 70\ kW/m^2; p = 7.75\ MPa$$

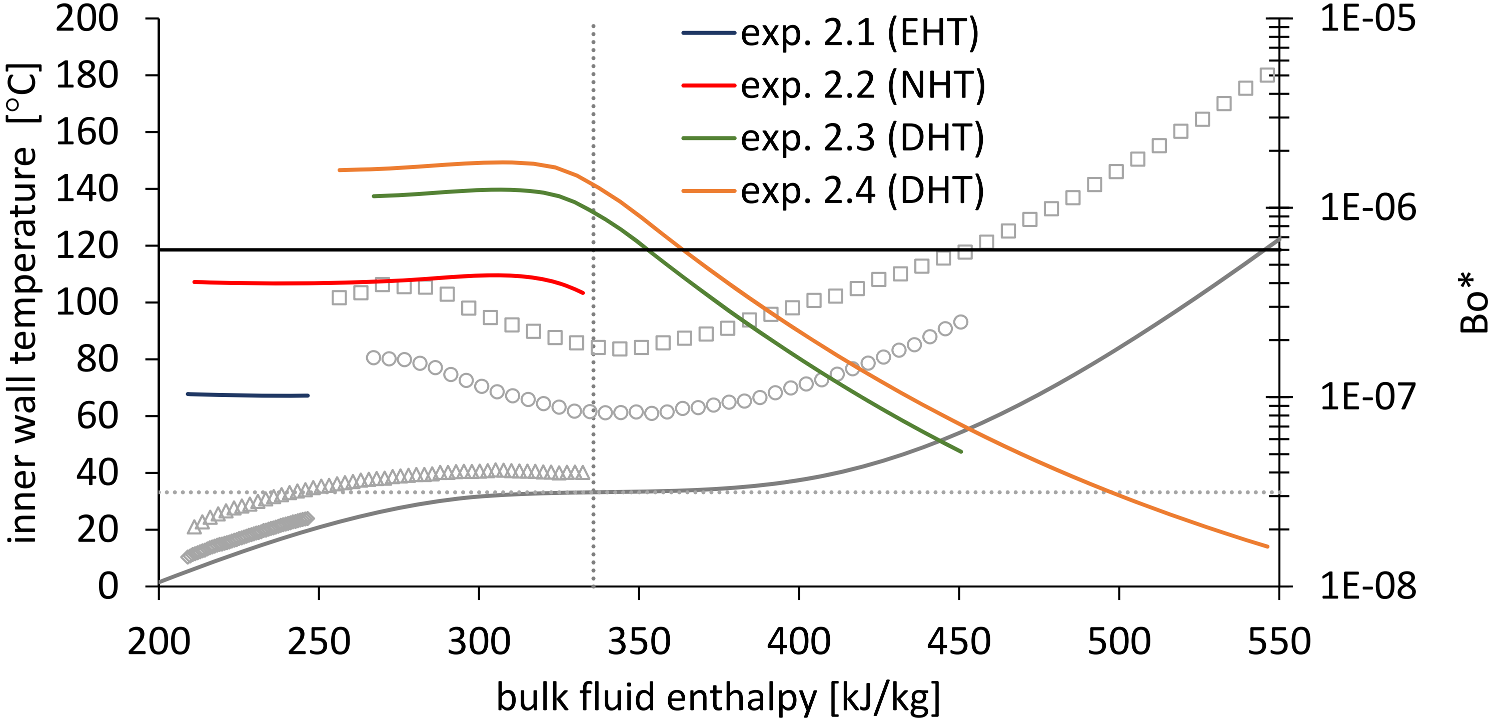


criterion in compliance with 3/4 experiments

Results

second test series – criterion based on buoyancy (McEligot and Jackson)

$d_i = 4\ mm; G = 400 kg/m^2 s;\ \dot{q} = 10, 30, 50, 70\ kW/m^2; p = 7.75\ MPa$

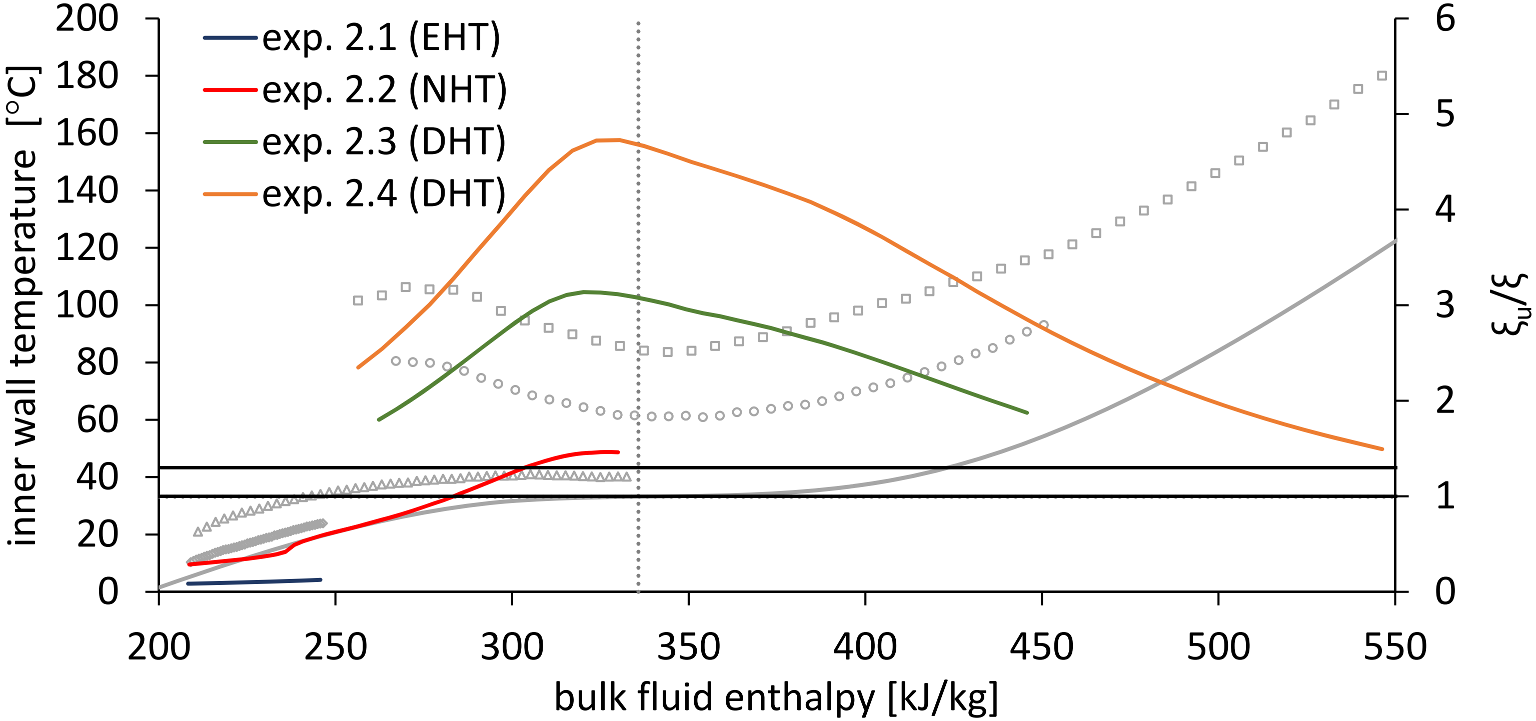


criterion in compliance with 4/4 experiments

Results

second test series – criterion based on flow acceleration (Petukhov et al.)

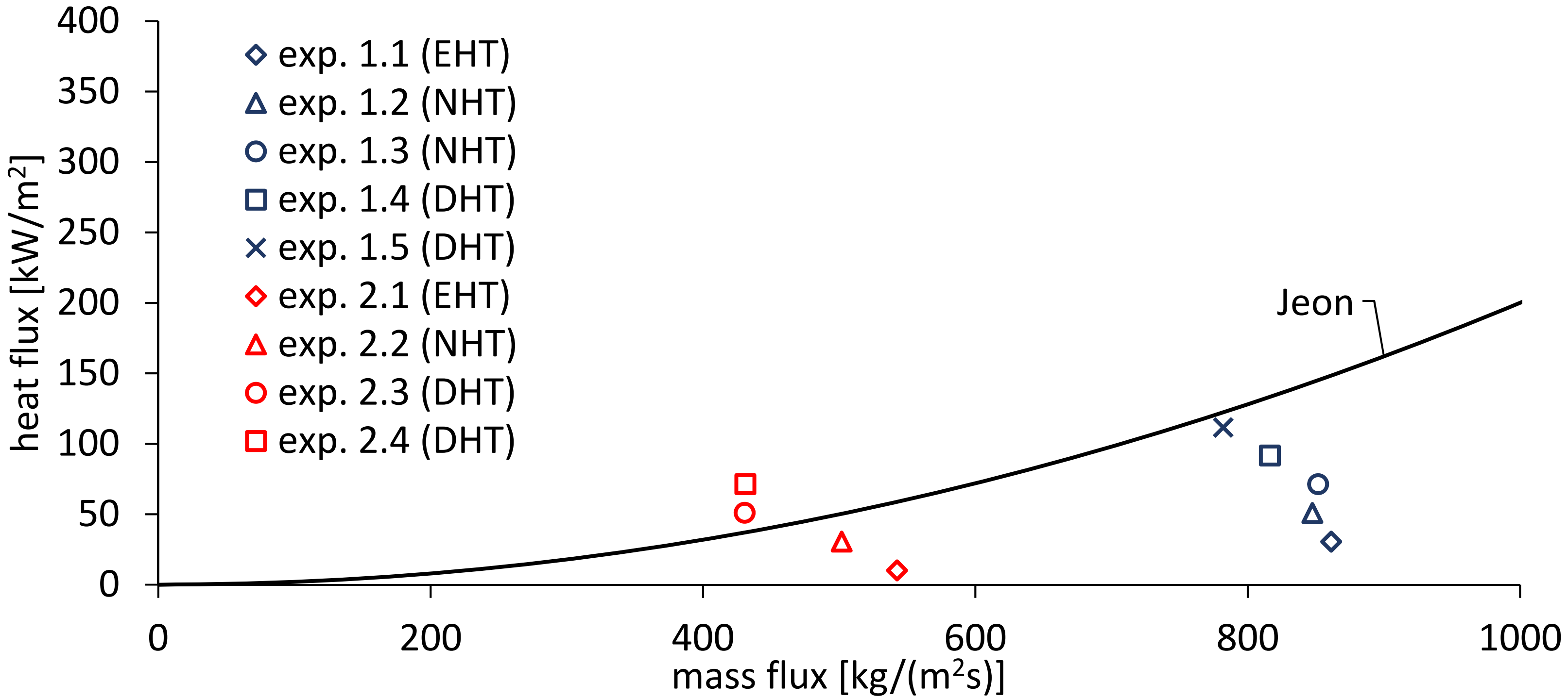
$d_i = 4\,mm; G = 400 kg/m^2s;\ \dot{q} = 10, 30, 50, 70\ kW/m^2; p = 7.75\ MPa$



criterion in compliance with 3/4 experiments

Results

first and second test series – criterion based heat flux to mass flux ratio (Jeon et al.)



criterion in compliance with 7/9 experiments

Summery & Conclusion

- experiments were carried out with a 4 mm heated single circular tube in a upward flow orientation to investigate different criteria for the onset of DHT
- four different criteria was tested with 9 experiment
- the compliance is as follows:
  - criterion based on buoyancy (Jackson et al.): 8/9
  - criterion based on buoyancy (McEligot and Jackson): 7/9
  - criterion based on flow acceleration (Petukhov et al.): 6/9
  - criterion based on heat flux to mass flux ratio (Jeon et al.): 7/9
- finally, it can be said that the Jackson criterion has the highest compliance with the here presented experiments

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Thank you!

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Data reduction

hydraulic inflow length

- sensors: Keller PD-33X, PA-33X
- hydraulic inflow length by Munson et al.:

$$L_{hyd} = \frac{L_{hyd}}{R} = 8{,}8 * Re^{\frac{1}{6}}$$

- 4 mm: max. Re_r= 200000

  → ca. 34*D → 150 mm

- 8 mm: max. Re_r= 400000

  → ca. 38*D → 320 mm