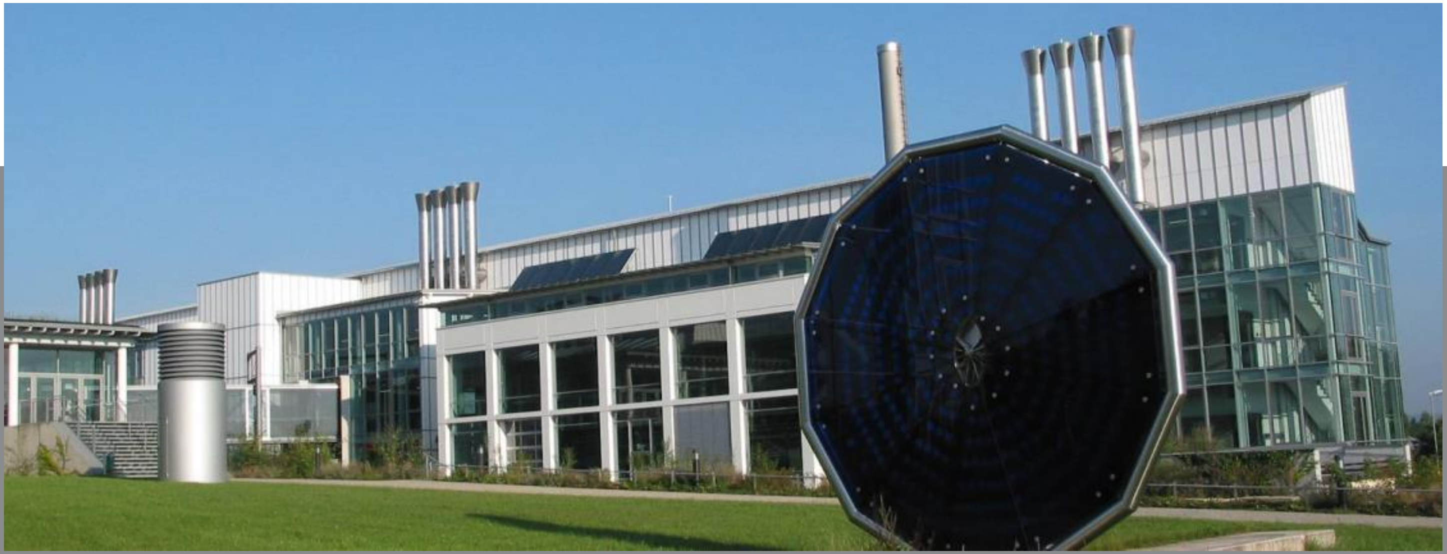

EXPERIMENTAL INVESTIGATIONS OF HEAT TRANSFER CHARACTERISTCS AND THERMAL STABILITY OF SILOXANES

2nd International Seminar on ORC Power Systems, Rotterdam (Netherlands)

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LEHRSTUHL FÜR TECHNISCHE THERMODYNAMIK UND TRANSPORTPROZESSE PROF. DR.-ING. D. BRÜGGEMANN

ZET Zentrum für Energietechnik

Introduction

Siloxanes as working fluids in ORC Power Systems

- Siloxanes are potential working fluids for ORC power systems.
- Advantages: long-term experiences, low toxicity and GWP = 0.
- Mainly used as ORC working fluids for high-temperature heat sources like biomass-fired power plants or waste heat recovery units.

Experimental investigation

Heat transfer coefficient

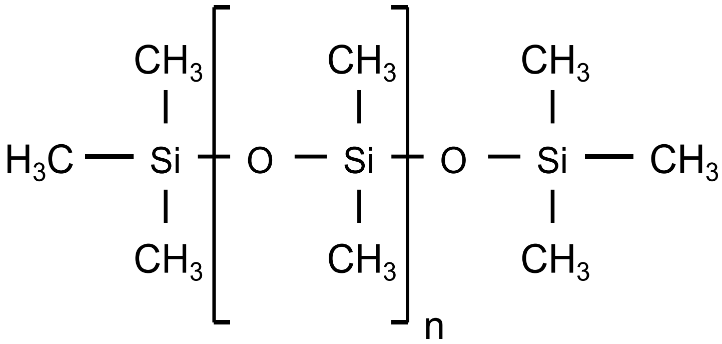
- Comparison to correlations
- Economic evaluation (pure fluids and mixtures)

Thermal stability

- Maximum process temperatures
- Decomposition products

Introduction
Investigated working fluids

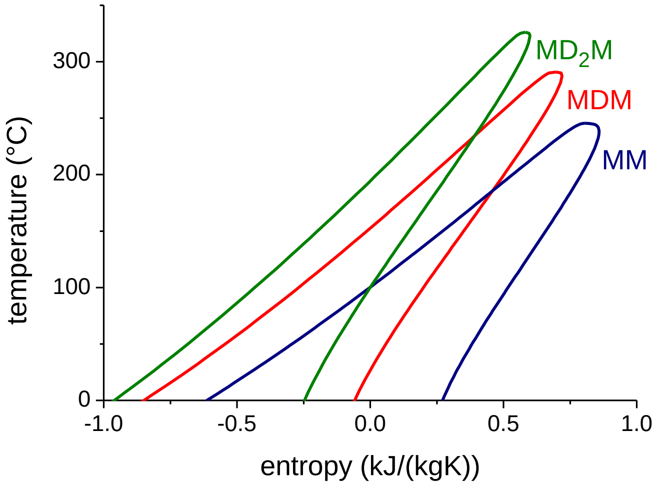
- Hexamethyldisiloxane (MM); n = 0
- Octamethyltrisiloxane (MDM); n = 1
- Decamethyltetrasiloxane (MD_2M); n = 2



Fluid properties:

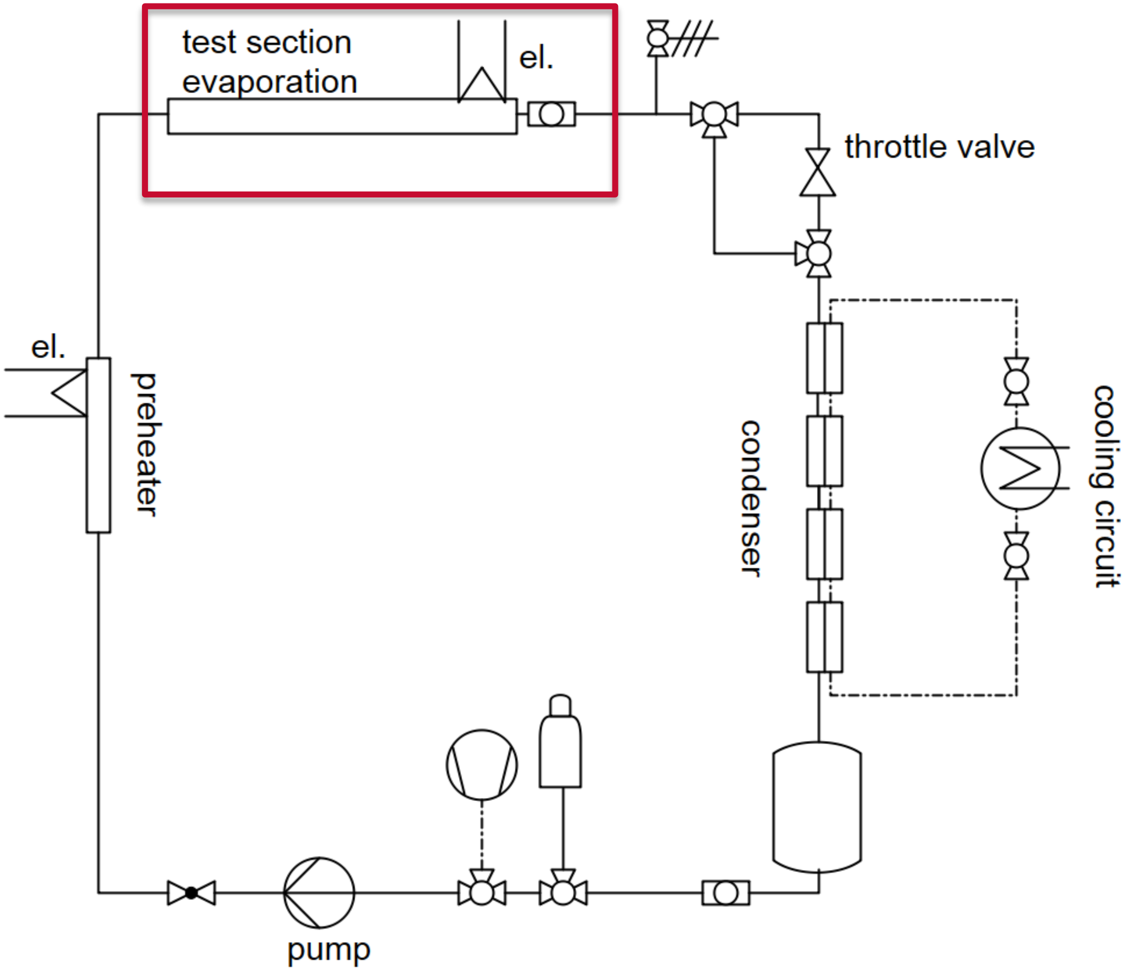
	Structural formula	T_{crit} (°C)	p_{crit} (bar)
MM	$C_6H_{18}OSi_2$	245.6	19.4
MDM	$C_8H_{24}O_2Si_3$	290.4	14.2
MD_2M	$C_{10}H_{30}O_3Si_4$	326.3	12.3

T,*s*-diagram:



Heat transfer characteristics

Experimental setup



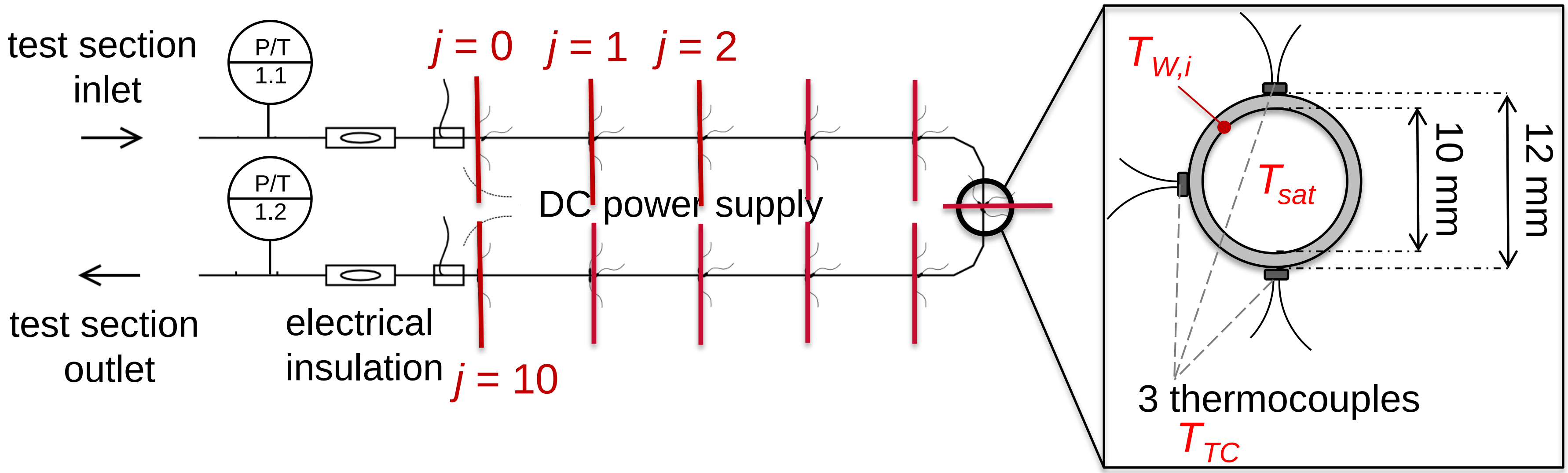
- p_{max} = 25 bar
- T_{max} = 260 °C

Test conditions:

- $\dot{q}$ = 8 – 18 kW/m^2
- G = 50 – 400 kg/(m^{2}s)
- Electrical heated steel pipe (DC power)
- Length: 5 m

Heat transfer characteristics

Evaporation – Test section



Data reduction:

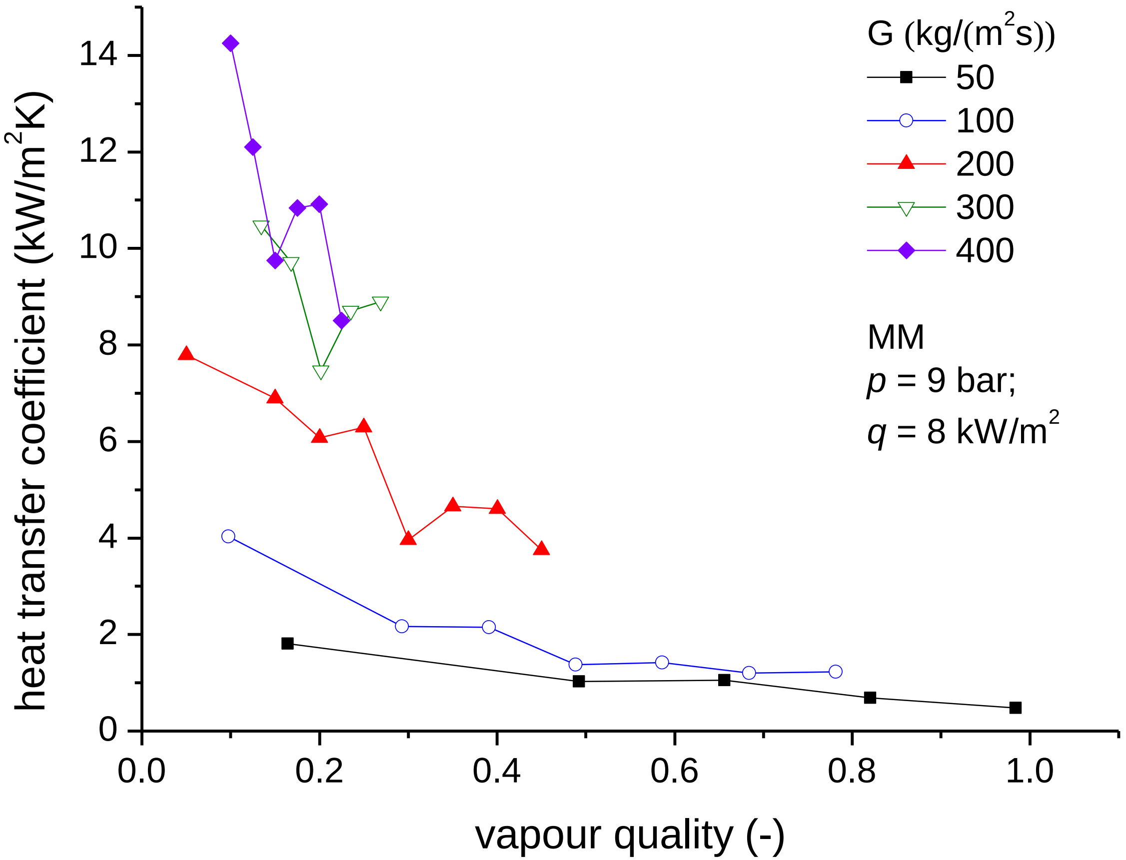
$$h_j = \frac{\dot{q}}{T_{W,i} - T_{sat}(p)}$$

$$T_{W,i} = \bar{T}_{W,o} + \frac{\dot{q}_i}{4\lambda} \cdot ({r_o}^2 - {r_i}^2) + \frac{\dot{q}_i}{2\lambda} \cdot ln\left(\frac{r_i}{r_o}\right) \cdot {r_o}^2$$

$$\bar{T}_{W,o} = \frac{T_{TC,top} + 2 \cdot T_{TC,middle} + T_{TC,bottom}}{4}$$

Results

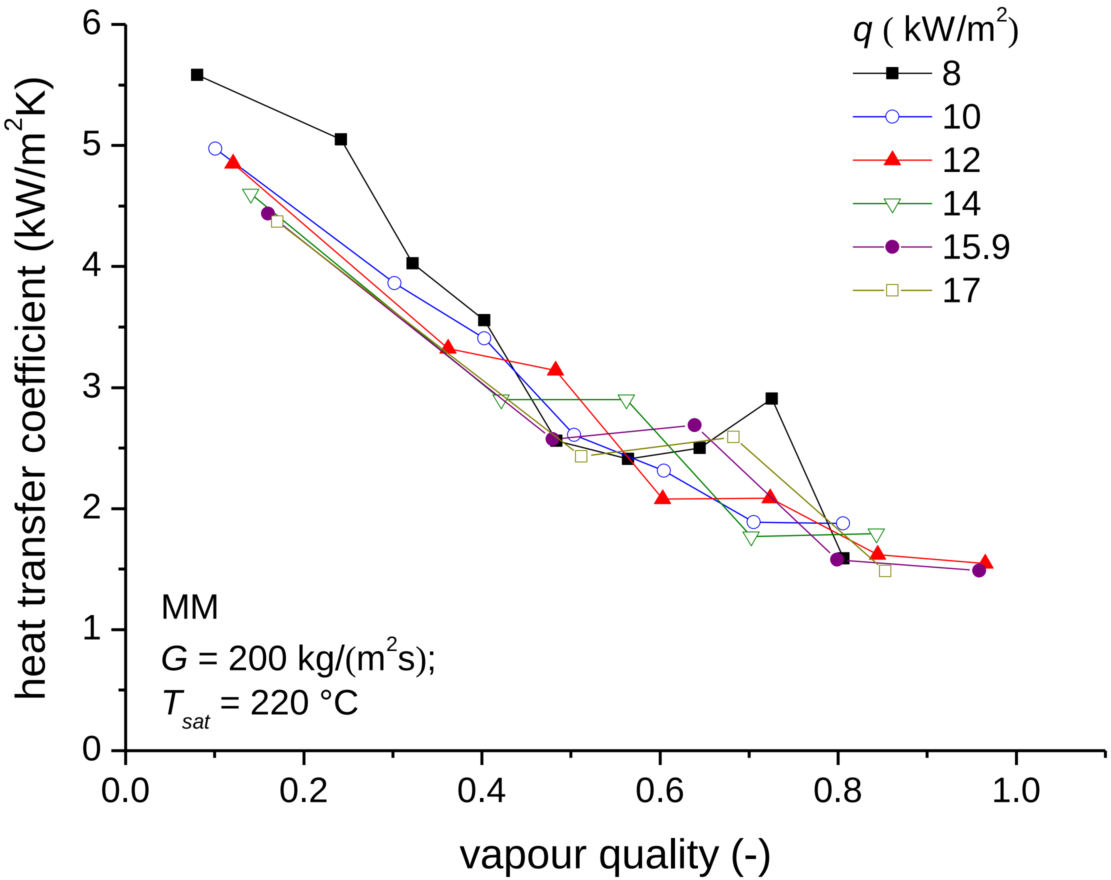
Variation of mass flux density – MM



- *h* increases with increasing mass flux density
- *h* decreases with increasing vapour quality

Results

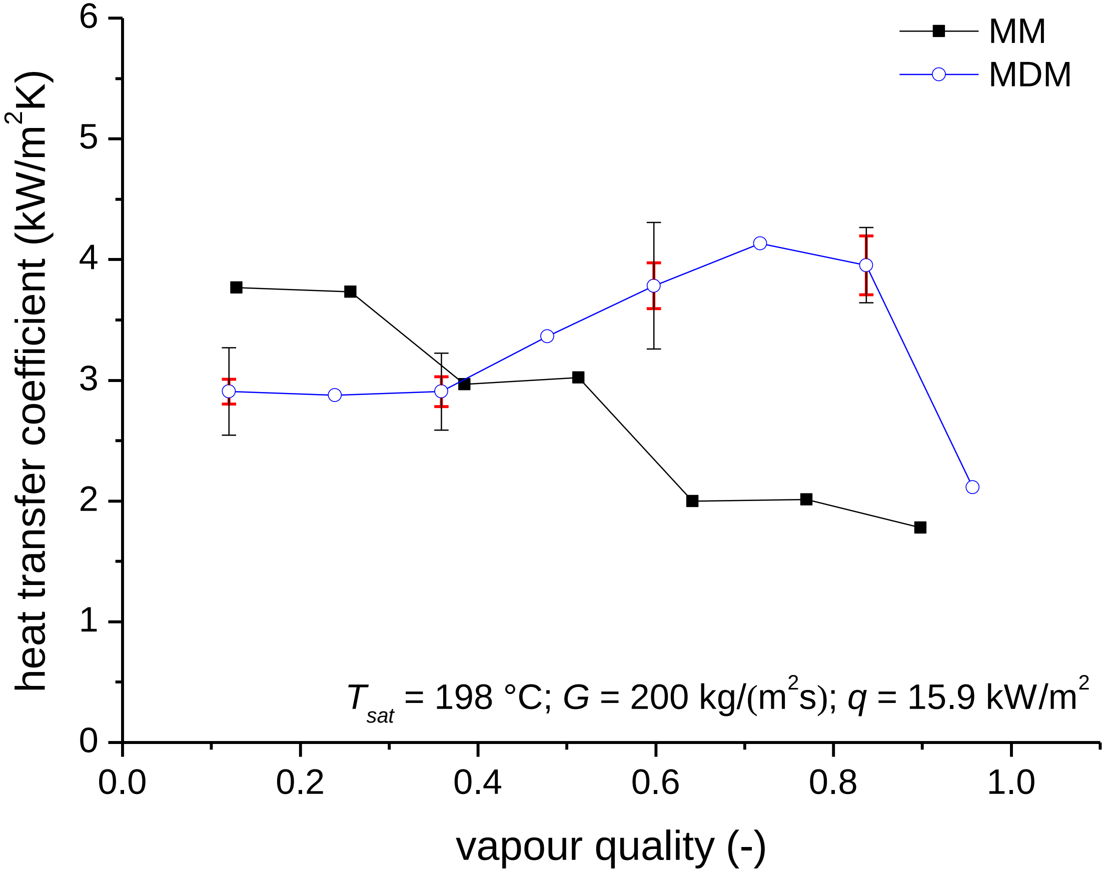
Variation of heat flux density – MM



- No significant influence of heat flux density
- *h* decreases with increasing vapour quality

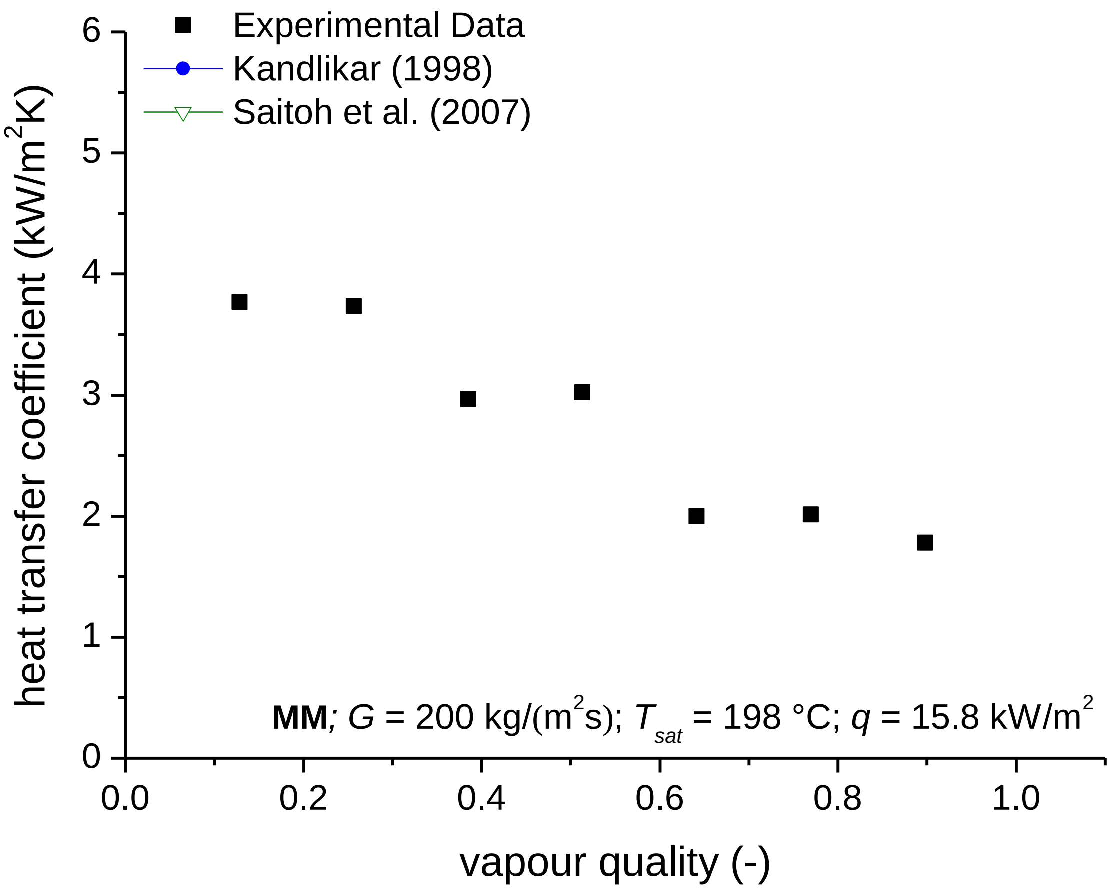
Results

Variation of examined working fluid – statistical and systematic uncertainties

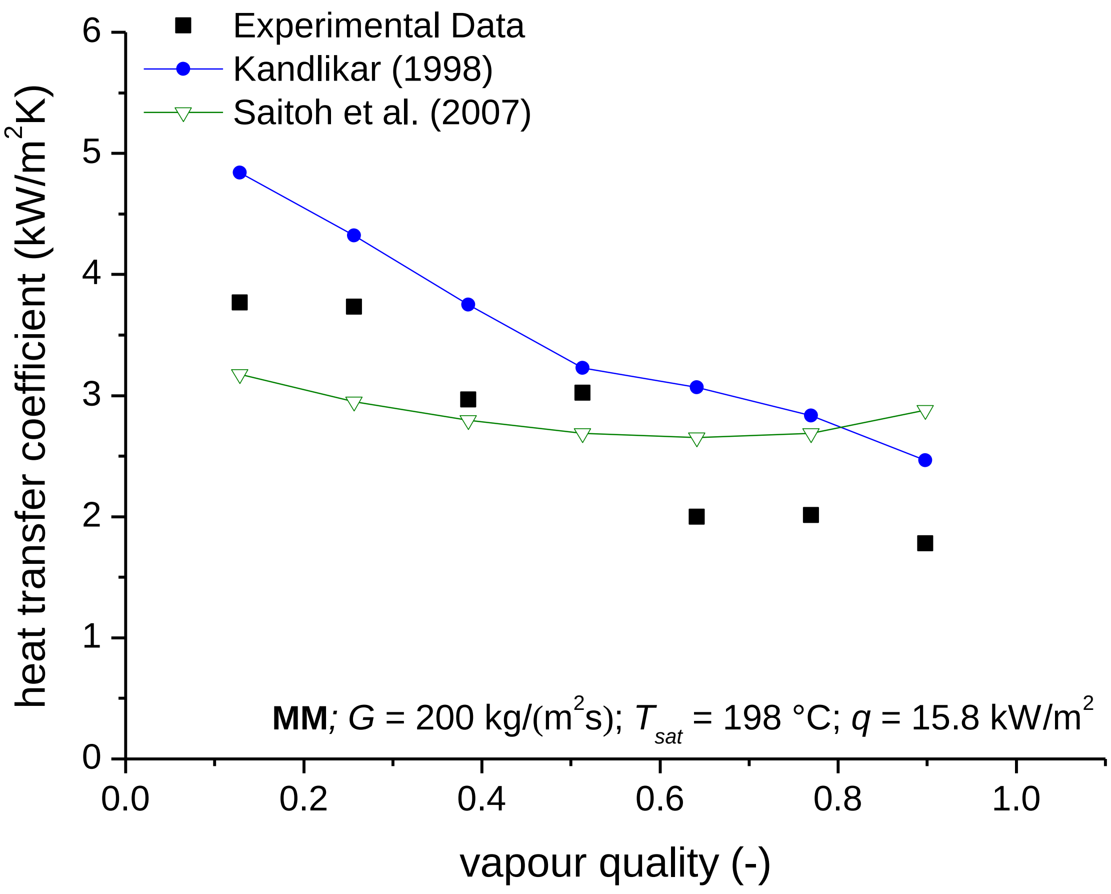


- Different behaviour of MM and MDM depending on vapour quality
- Statistical uncertainties (5 repetitions)
- Systematic uncertainties ($\Delta A/A$; $\Delta P/P$, $\Delta T_{W,o}/T_{W,o}$, $\Delta p_{sat}/p_{sat}$)

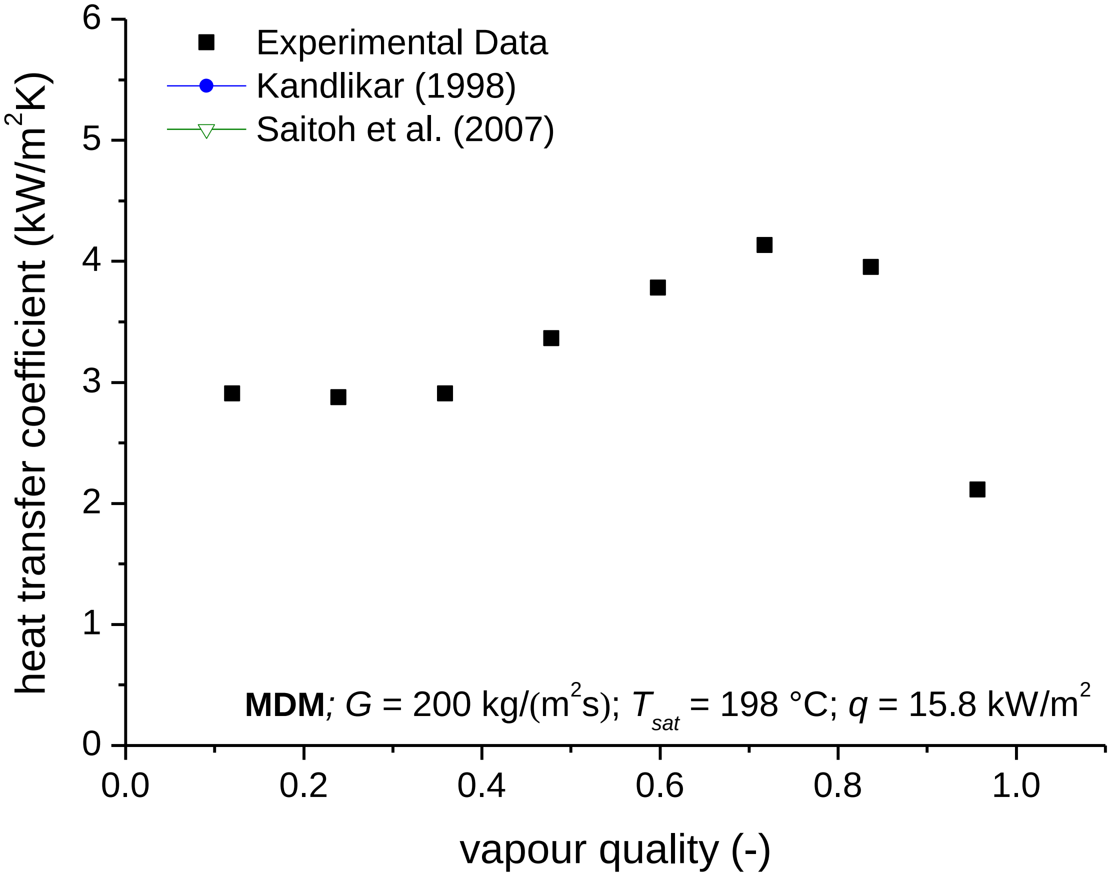
Results
Comparison to correlations



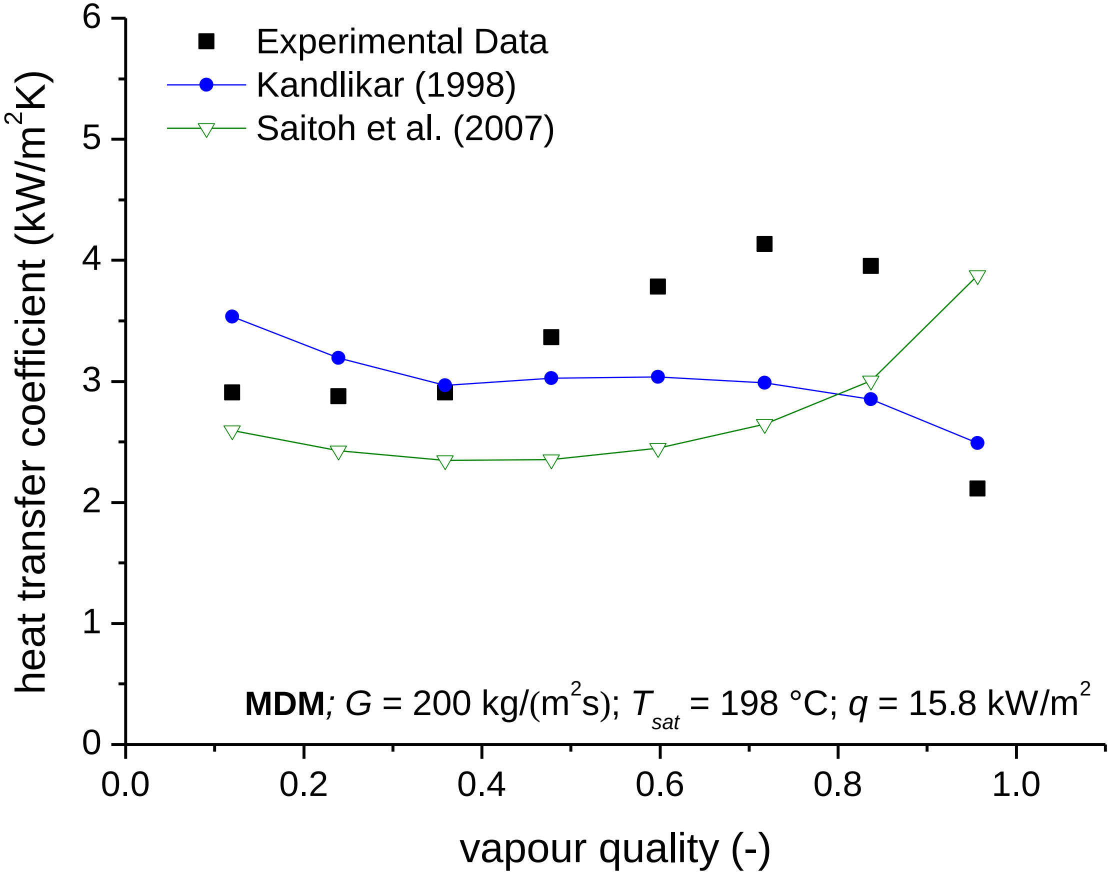
Results
Comparison to correlations



Results
Comparison to correlations

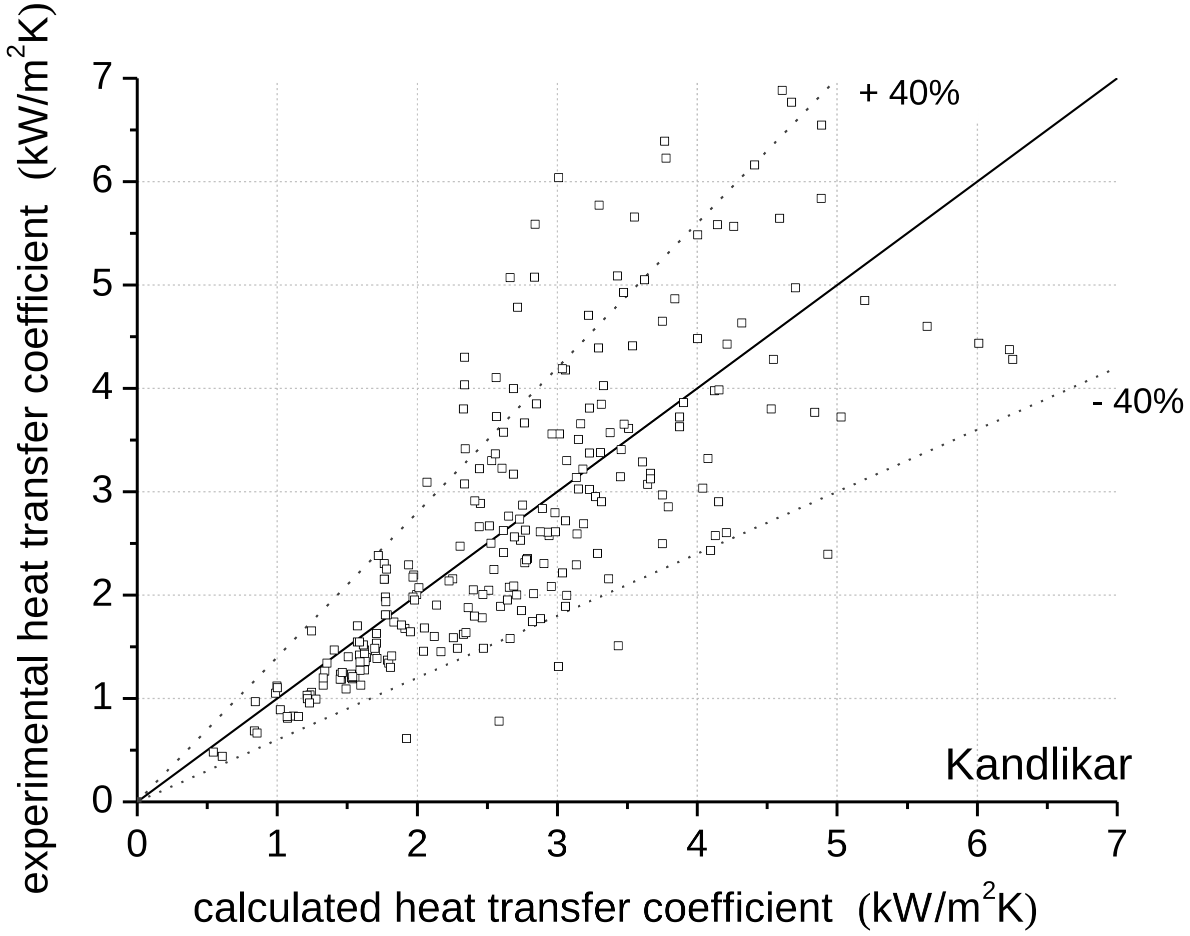


Results
Comparison to correlations



Results

Comparison to correlations – working fluid: MM



- All measured local *h*
- Mean relative deviation (Kandlikar) **25.1 %**
- Saitoh et al. **49.0 %**
- Mean relative deviation (MDM – Kandlikar) **40.9 %**

Heat transfer measurements

Main results

- Heat transfer coefficients are measured for process temperatures up to 250 °C.
- Empirical model of Kandlikar shows a good agreement to the experimental data.

Experimental investigation

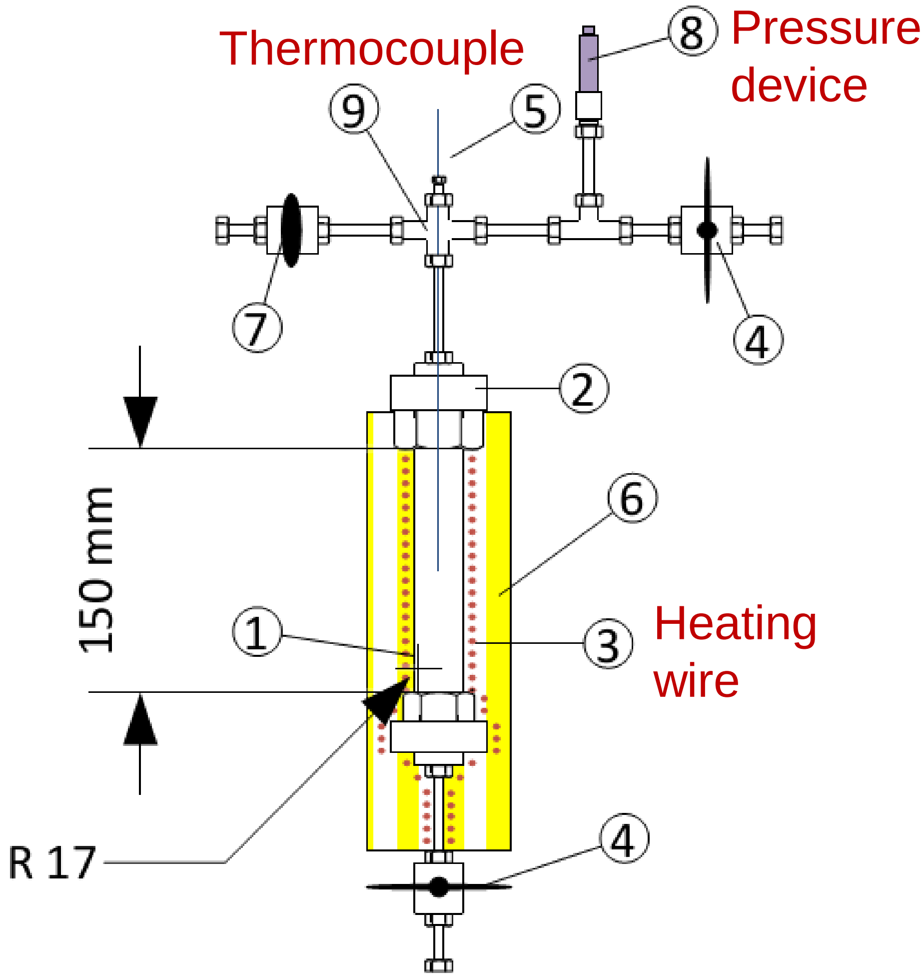
Heat transfer coefficient

- Comparison to correlations
- Economic evaluation (pure fluids and mixtures)

Thermal stability

- Maximum process temperatures
- Decomposition products

Thermal stability
Experimental setup



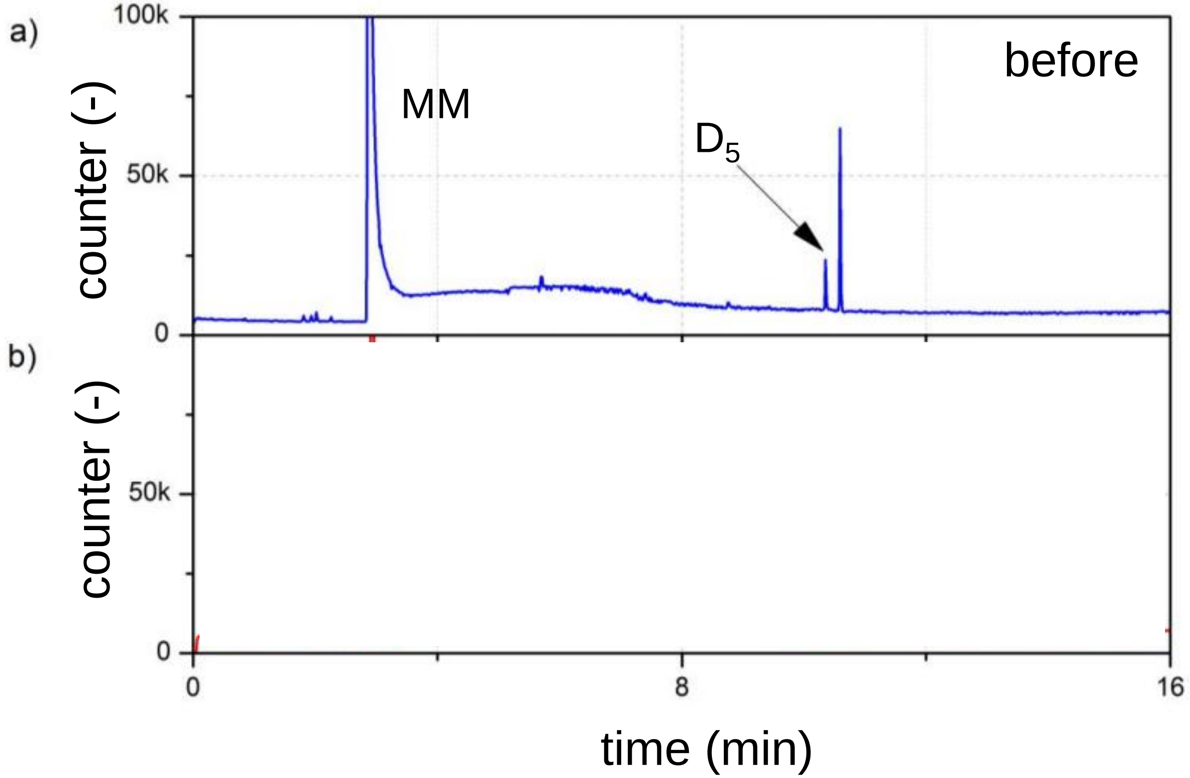
- p_{max} = 30 bar
- T_{max} = 500 °C

Test conditions:

- t = 72 h
- T = 240 – 420 °C
- Electrical heated by heating wire
- Analysed by gas chromatography/ mass spectroscopy

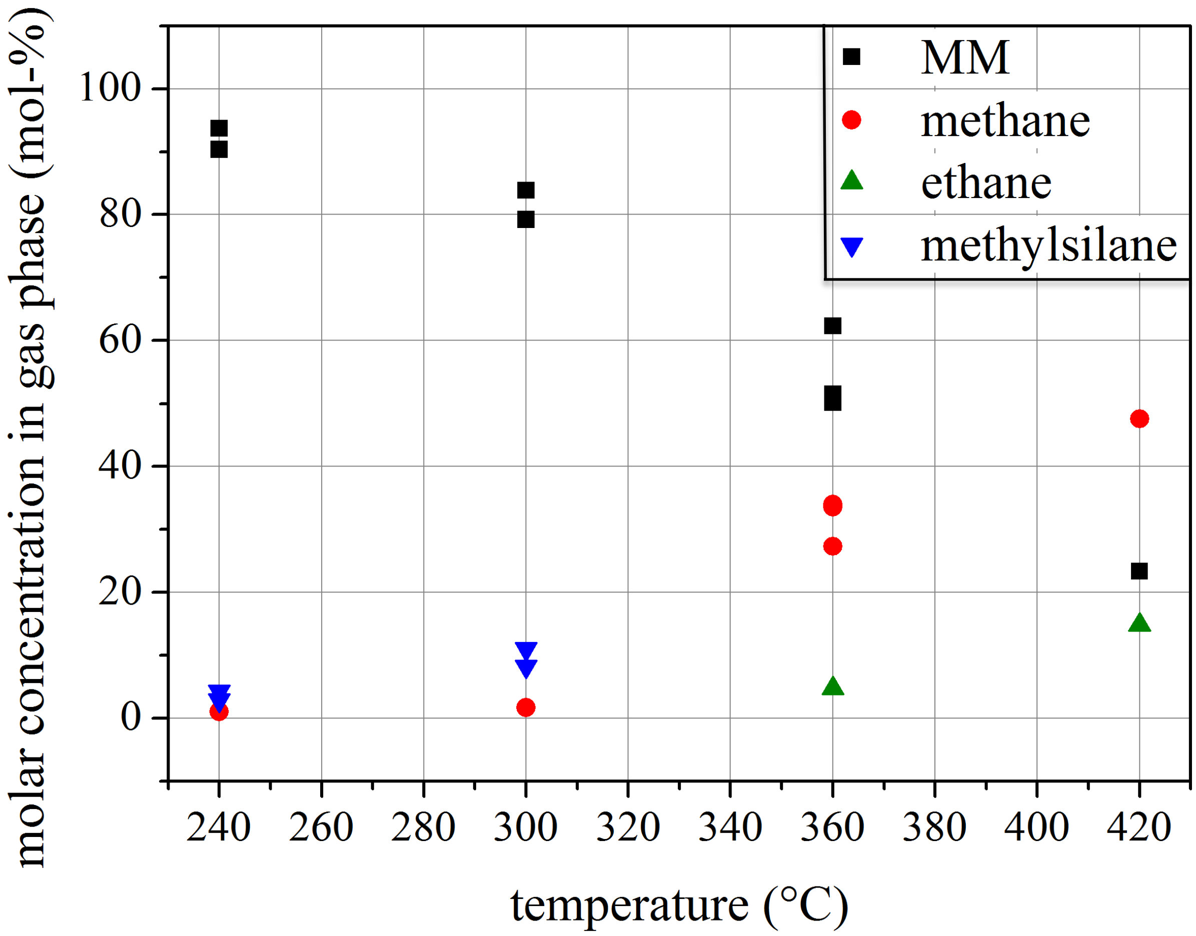
Results

Liquid phase, 360 °C, 144 h



- Fluid: Wacker® AK 0.65
- Purity: > 97 mass-%
- Formation of higher chained siloxanes in accordance to *Dvornic, Gelest, Inc.*

Results
Gas phase, 72 h



- Averaged molar concentration before tests: 99.4 mol-%
- Formation of methane and ethane in accordance to *Manders and Bellama, Journal of Polymer Science, 1985*

Conclusions and Future work

- Heat transfer and thermal stability measurements were carried out for selected siloxanes.
- The correlation of Kandlikar shows the best agreement to experimental data.
- No significant amount of decomposition products for heat transfer test conditions.

- Heat transfer characteristics of the mixture MM/MDM and MM/MDM/MD_2M.
- Investigation of enhanced tubes and alternative working fluids.
- Long-term and dynamic tests concerning thermal stability.

Acknowledgements

The authors gratefully acknowledge financial support from

DFG

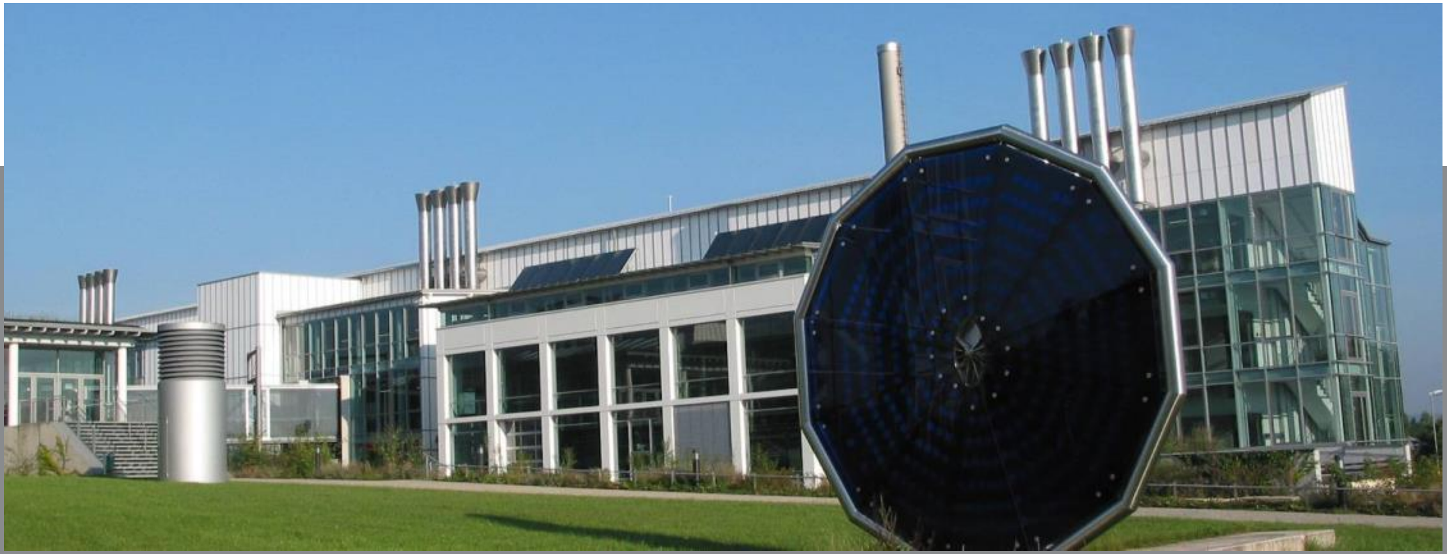
“Fluid mixtures for efficiency increase of Organic Rankine Cycles in selected applications” (Grant no. 1713/12-1 and -2)

TAO

Partial financing of the thermal stability test rig

WACKER

Free provision of Wacker® AK 0.65



Thank you

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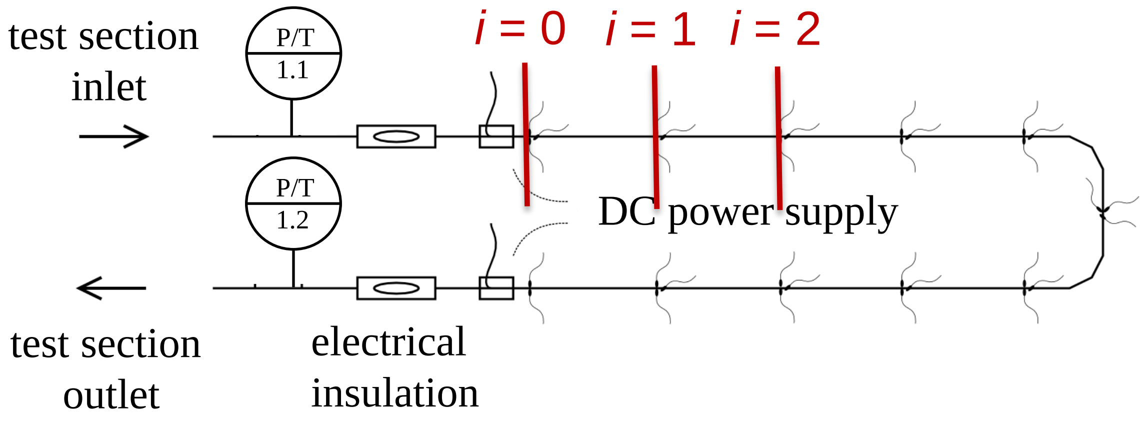
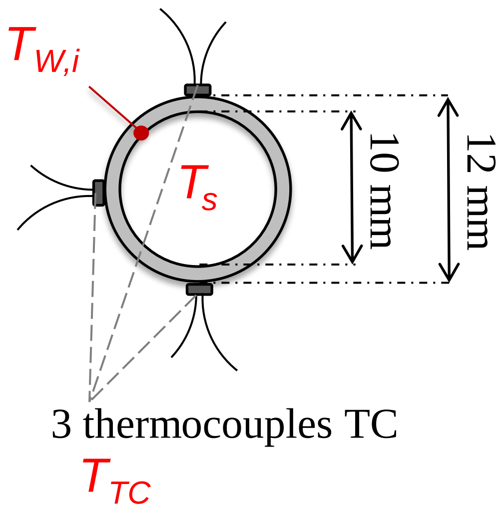
Heat transfer characteristics
Evaporation – Test section





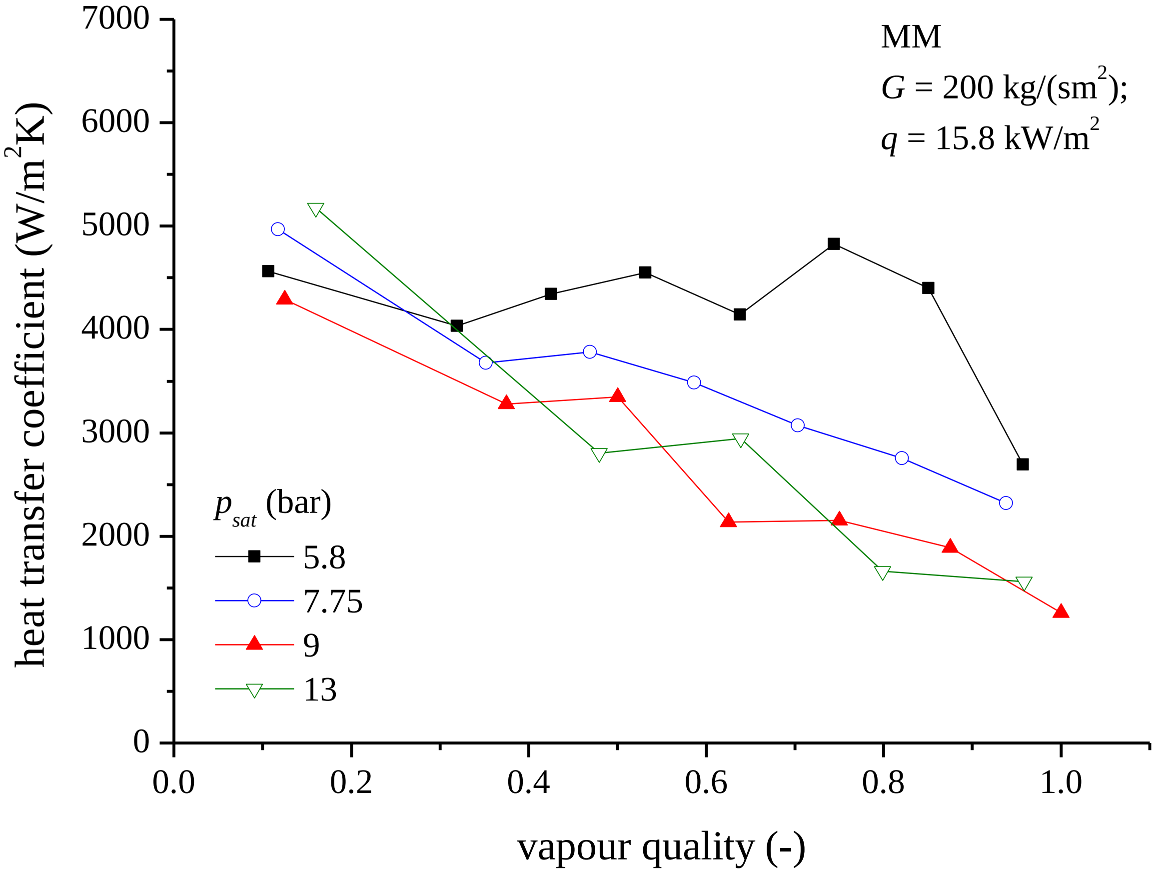
Data reduction:

$$x_i = \frac{h_i - h'}{h'' - h'} \qquad i = 1 - 10$$

$$h_i = h_{i-1} + \Delta h = h_{i-1} + \frac{P_i}{\dot{m}_{TF}} \qquad h_0 = h(T_{sat} - 0.5K) \rightarrow \text{subcooled}$$

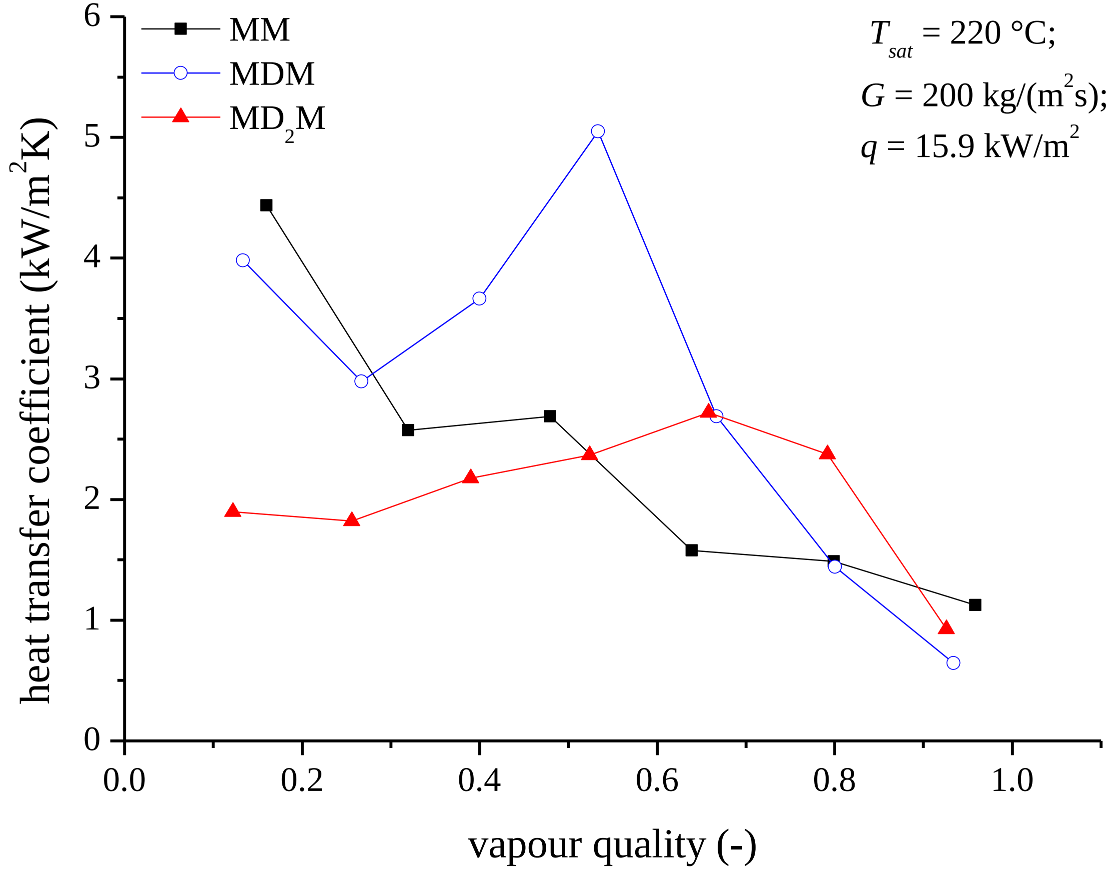
Results

Variation of saturation pressure- MM



Results

Variation of examined working fluid



Results

Comparison to correlations – Model of Kandlikar

$$htc_{\mathrm{tp}} = \begin{cases} htc_{\mathrm{tp,nbd}} \\ htc_{\mathrm{tp,cbd}} \end{cases}$$

$$htc_{\mathrm{tp,nbd}} = 0.6683 \cdot Co^{-0.2} \cdot (1-x)^{0.8} \cdot htc_{\mathrm{LO}} + 1058 \cdot Bo^{0.7} \cdot (1-x)^{0.8} \cdot F_{\mathrm{fl}} \cdot htc_{\mathrm{LO}}$$

$$htc_{\mathrm{tp,cbd}} = 1.136 \cdot Co^{-0.9} \cdot (1-x)^{0.8} \cdot htc_{\mathrm{LO}} + 667.2 \cdot Bo^{0.7} \cdot (1-x)^{0.8} \cdot F_{\mathrm{fl}} \cdot htc_{\mathrm{LO}}$$

$$htc_{\mathrm{LO}} = \frac{\left({}^{\zeta}/_{2}\right)(Re_{\mathrm{LO}} - 1000) \cdot Pr_{l}}{1{,}0 + 12{,}7 \cdot \sqrt{{}^{\zeta}/_{2}}\left(Pr_{\mathrm{l}}{}^{2/3} - 1\right)} \cdot \left(\frac{\lambda_{\mathrm{l}}}{d_{\mathrm{i}}}\right)$$

$$Bo = \frac{\dot{q}}{G \cdot \Delta h} = \frac{A_{\mathrm{cs}} \cdot \dot{q}}{\dot{m} \cdot (h'' - h')}$$

$$Co = \left(\frac{\rho_{\mathrm{g}}}{\rho_{\mathrm{l}}}\right)^{0{,}5} \left(\frac{1-x}{x}\right)^{0{,}8}$$

Results

Comparison to correlations – Model of Saitoh et al.

$$htc_{\mathrm{tp}} = F htc_l + S htc_{pool}$$

$$F = 1 + \left(\frac{1}{x}\right)^{1.05} + \left(1 + We_g{}^{-0.4}\right)$$

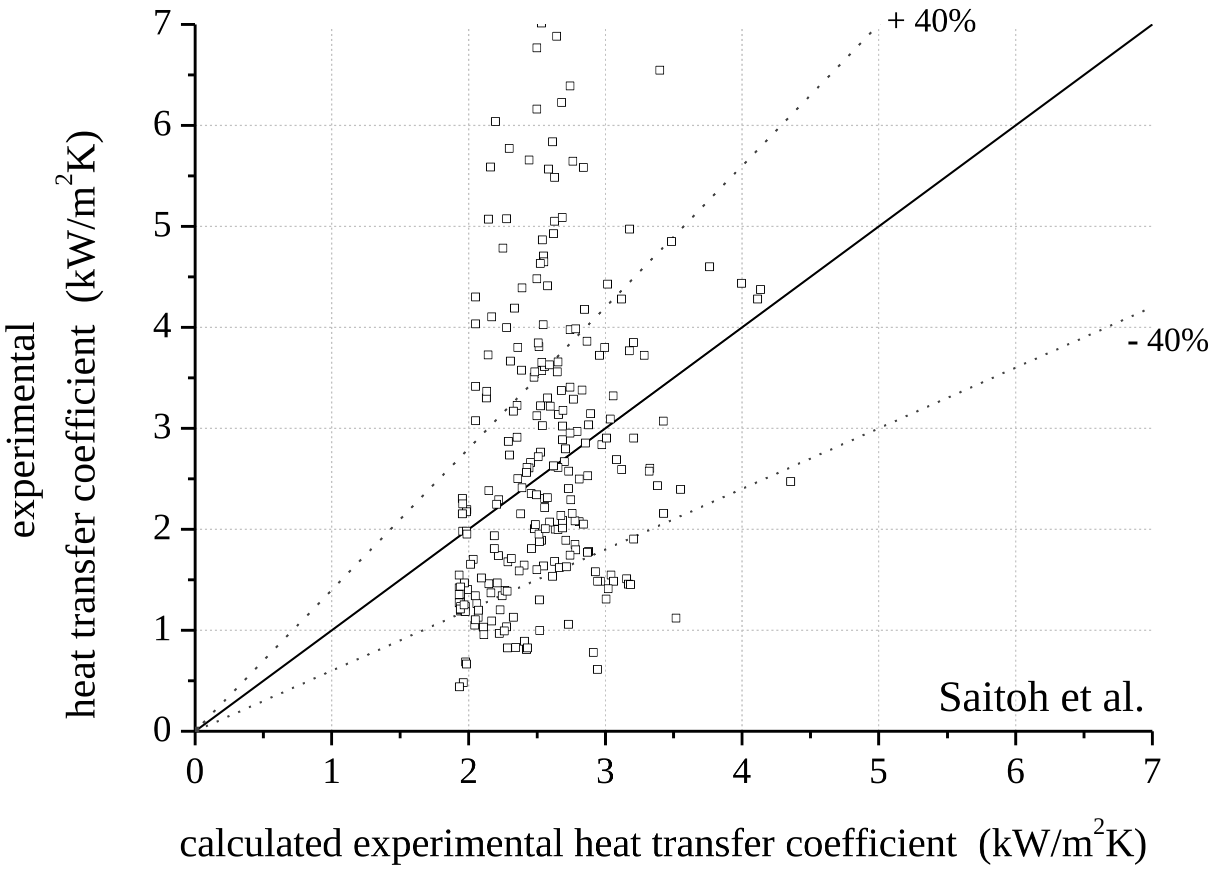
$$\mathrm{S} = 1/1 + \left(Re_{tp} \cdot 10^{-4}\right)^{1.405}$$

$$htc_l = 0.223\frac{\lambda_l}{D} \cdot \left(\frac{G(1-x)D}{\eta_l}\right)^{0.8} \cdot \left(\frac{c_{p,l}\eta_l}{\lambda_l}\right)^{0.8}$$

$$htc_{pool} = 207\frac{\lambda_l}{d_b} \cdot \left(\frac{\dot{q} d_b}{\lambda_l T_l}\right)^{0.745} \cdot \left(\frac{\rho_g}{\rho_l}\right)^{0.581} \cdot Pr_l{}^{0.533}$$

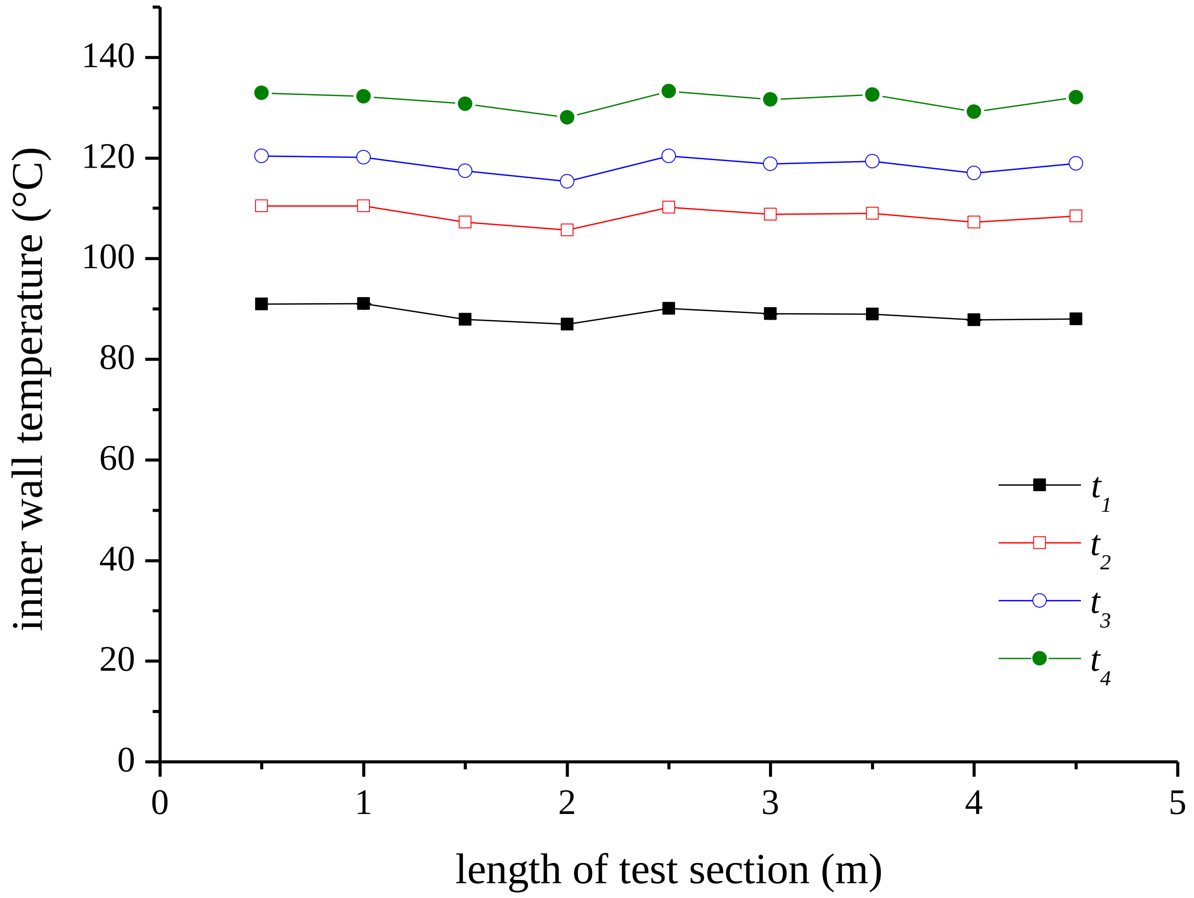
Results

Comparison to correlations – working fluid: MM

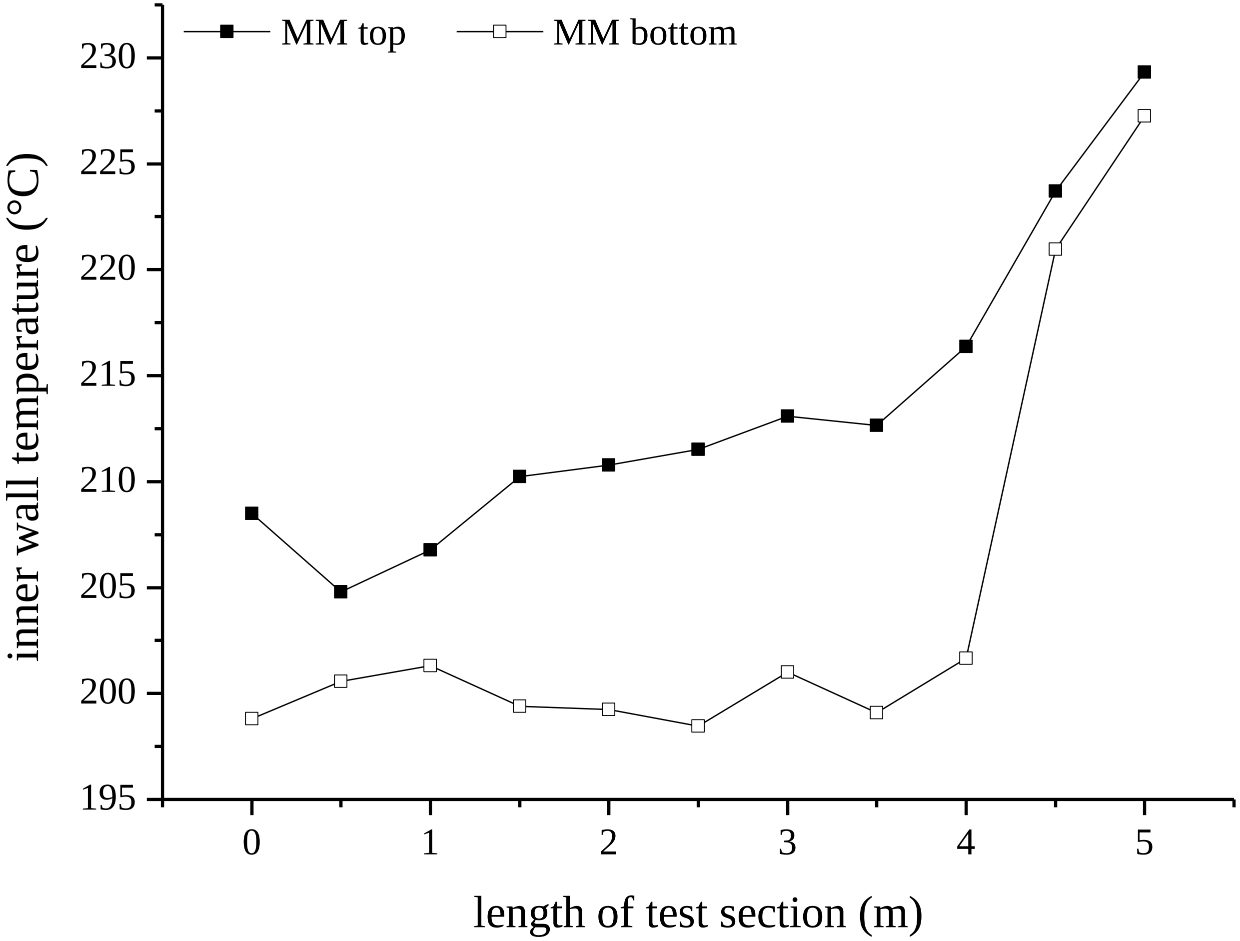


- Measured local *htc*
- Mean relative deviation (Kandlikar) **25,1 %**
- Saitoh et al. **49,0 %**

Results
Homogenous temperature profile

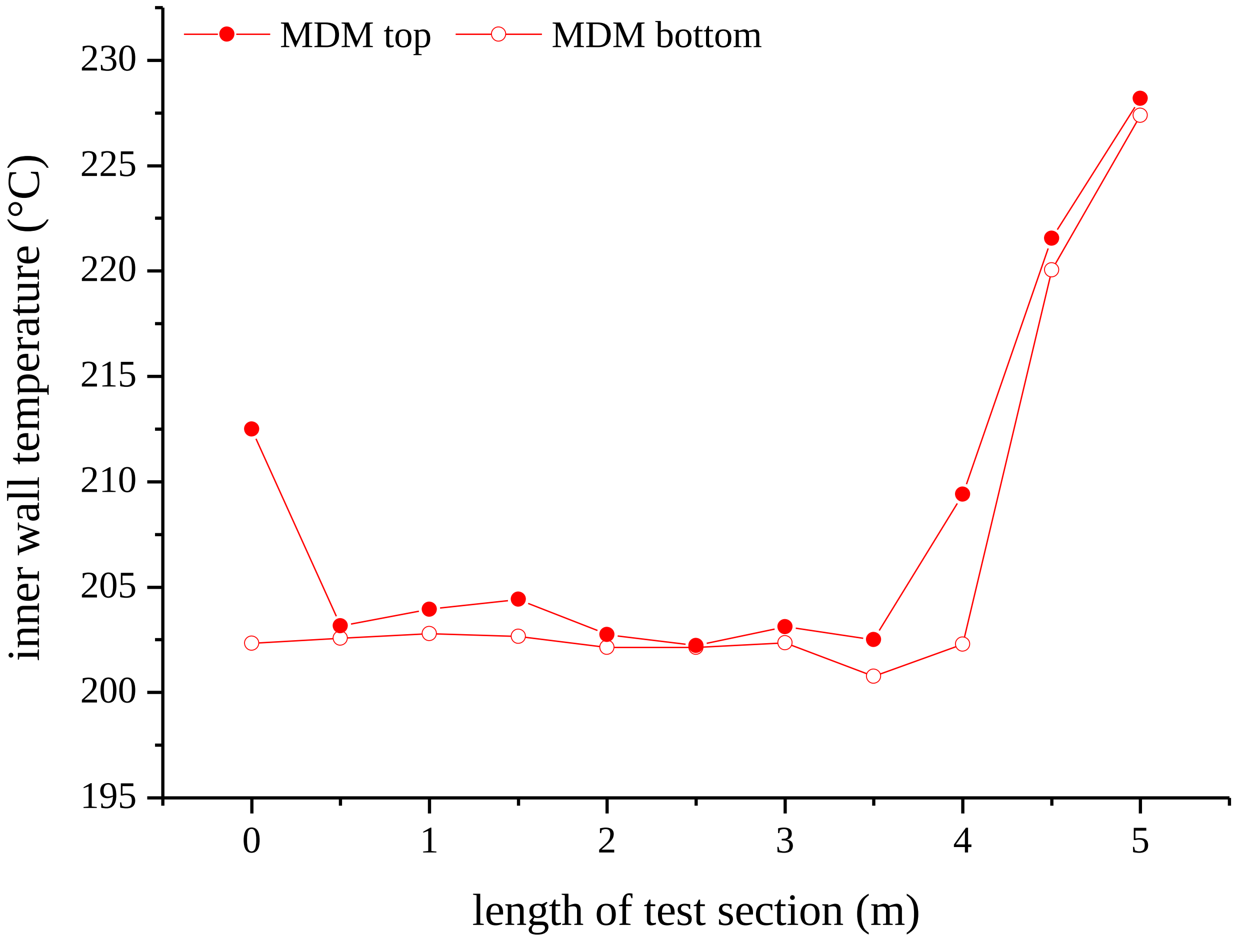


Results



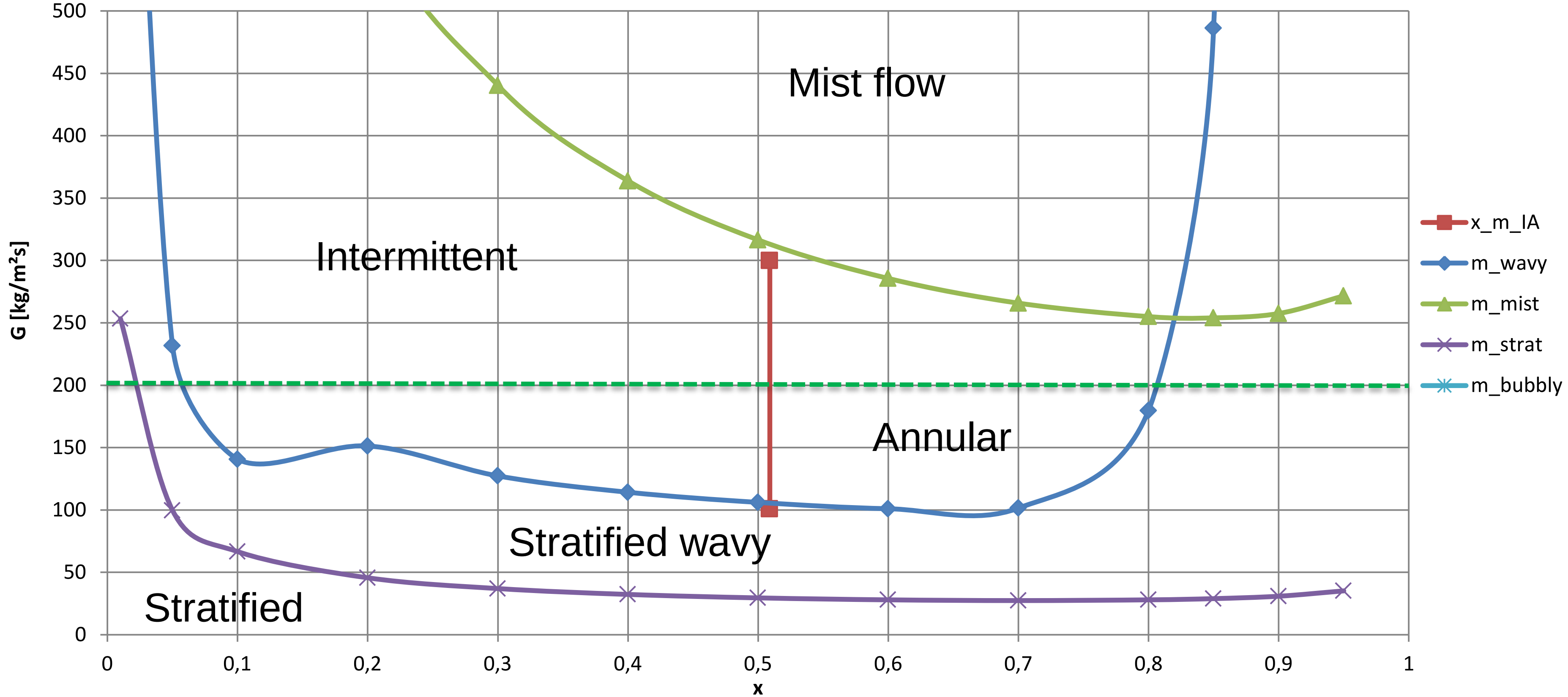
MM top
MM bottom
inner wall temperature (°C)
230
225
220
215
210
205
200
195
0
1
2
3
4
5
length of test section (m)

Results

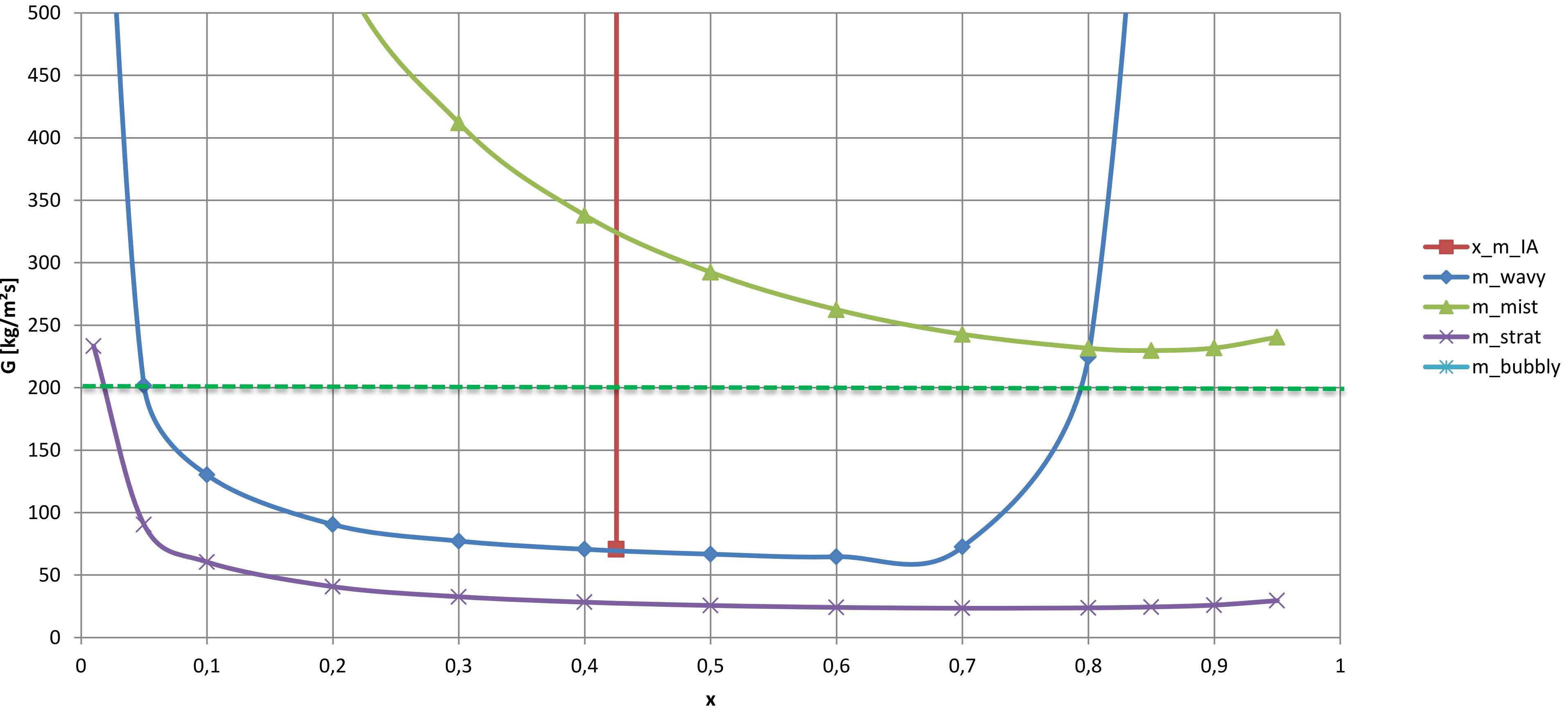


MDM top
MDM bottom
230
225
220
215
210
205
200
195
inner wall temperature (°C)
0
1
2
3
4
5
length of test section (m)

Results
Flow regimes - MM



Results
Flow regimes – MDM

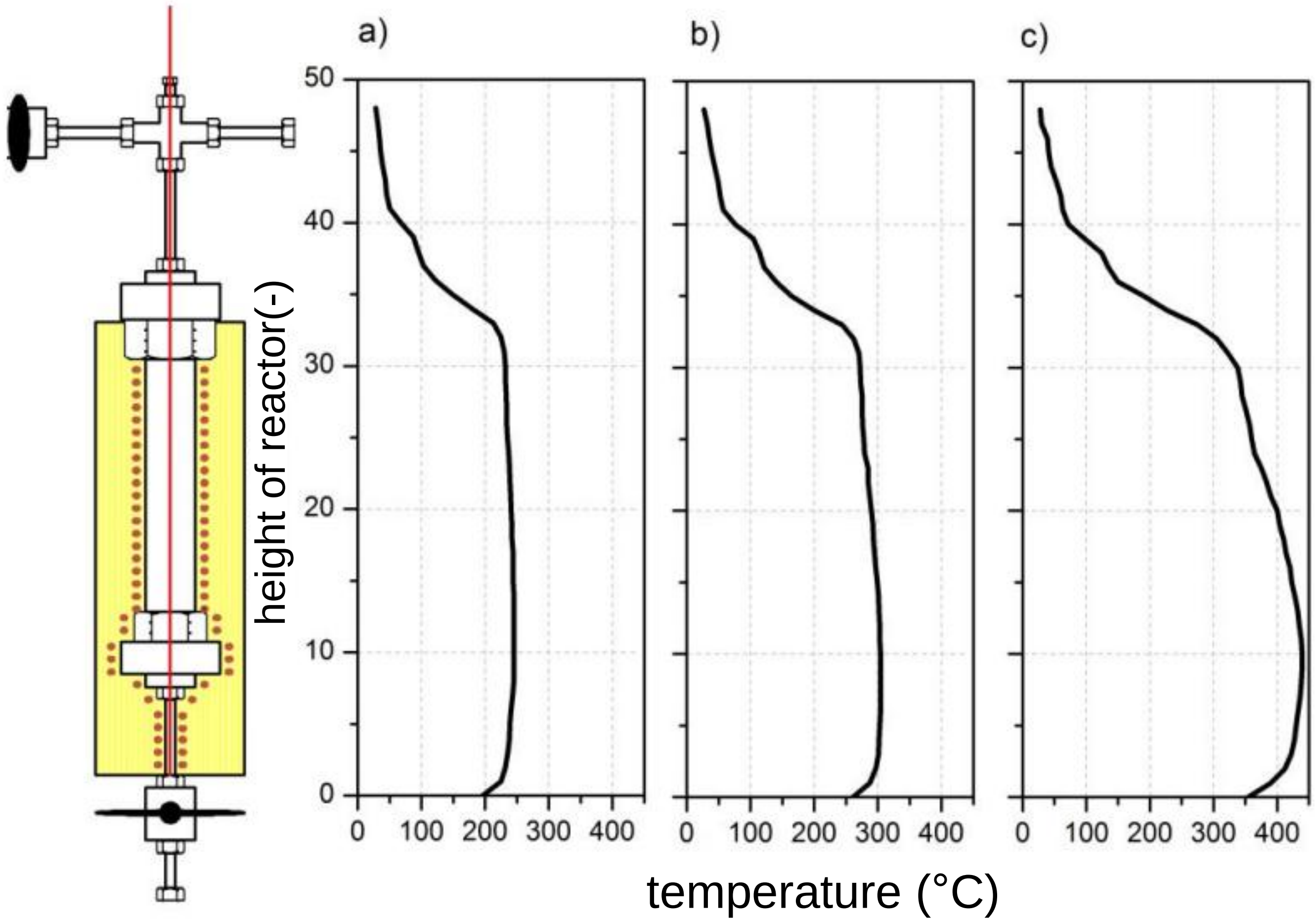


Results
Fluid properties

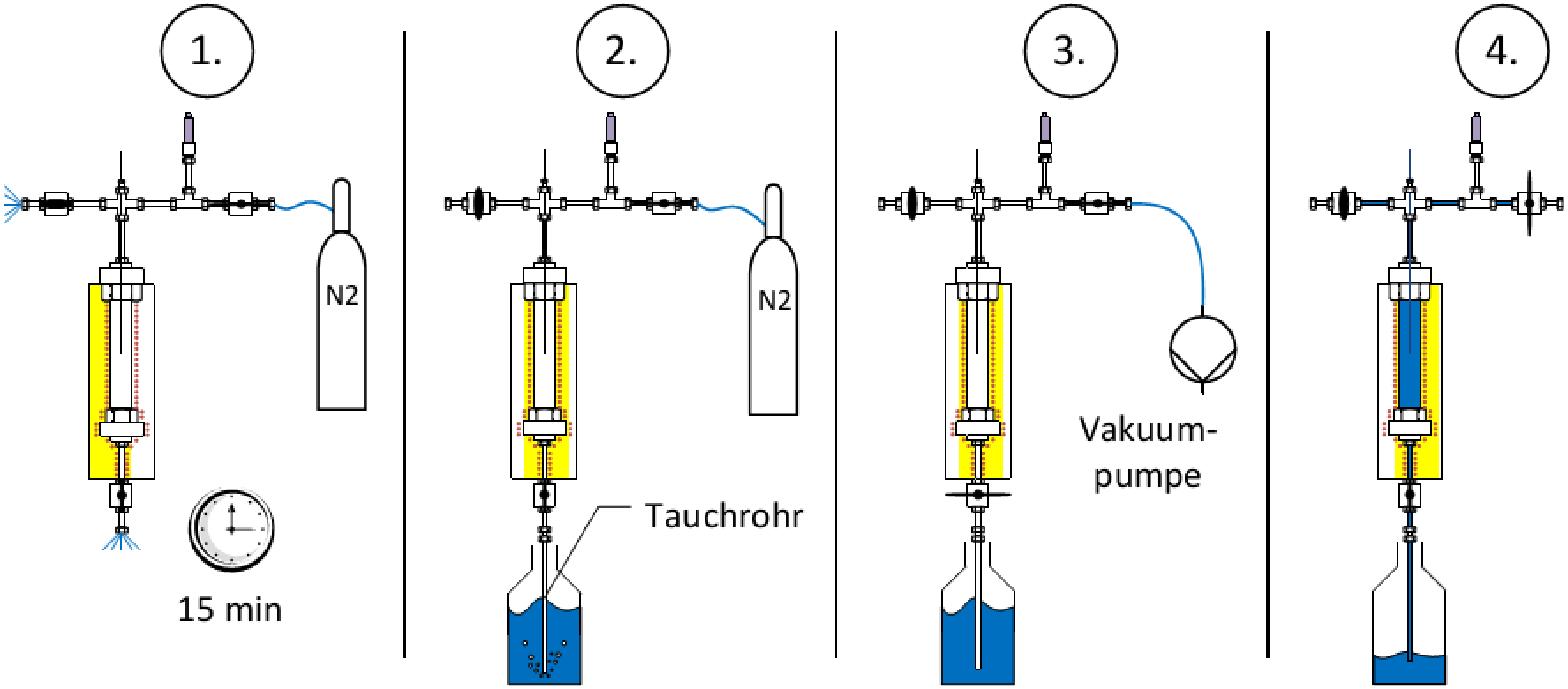
	p_{sat} (bar)	p_{red}	ρ_v (kg/m³)	ρ_l / ρ_v	σ (N/m)
MM	9.03	0.47	53.54	10.05	0.0154
MDM	2.90	0.21	20.82	29.44	0.0166

- Higher vapour density for MM → lower vapour velocity at same mass flux.
- Nucleate dominates at low vapour qualities, caused by low surface tension and liquid-to-vapour density ratio.
- Lower surface tension increase the probability of liquid entrainment in the vapour core.
- Suppression of nucleate boiling is delayed by higher vapour density (lower velocity

Thermal stability
Temperature distribution



Outline
Test procedure



Outline

Dynamic test rig