Methodology

of

MICRO Test Rig Measurements

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1 Introduction

This methodology report is part of the paper:

Thanheiser, S.; Haider, M.; Schwarzmayr, P. Experimental Investigation of the Heat Transfer between Finned Tubes and a Bubbling Fluidized Bed with Horizontal Sand Mass Flow. Energies 2021, 14, x. https://doi.org/10.3390/xxxxx

All data and supplementary documentation is published in the data repository:

https://doi.org/10.5281/zenodo.5802409

Software for data analysis can be found in the software repository:

https://doi.org/10.5281/zenodo.5802407

If not indicated otherwise, the references in square brackets refer to the manuscript references.

All calculations shown in this report are performed in the MATLAB script “Analyze_MICRO” in the software repository and are based on data in the data repository (all .csv-files starting with MICRO). The variable names are as close as possible to the variable names in the MATLAB script and data files while ensuring their readability in this report.

2 Measurements and Calculations

Constants

$l = 0.2\ \text{m}$	Fluidized bed length
$w = 0.2\ \text{m}$	Fluidized bed width
$l_{\text{heated}} = 0.1\ \text{m}$	Heated tube length
$d = 25\text{e-}3\ \text{m}$	Tube diameter
$A = d\,\pi\, l_{\text{heated}}$	Heated tube area
$d_{\text{p1}} = 87.141\text{e-}6\ \text{m}$ $d_{\text{p2}} = 210\text{e-}6\ \text{m}$	Mean diameter of the different particles used. The results of the laser diffraction analysis of the smaller diameter sand and the datasheet of the larger diameter sand are in the appendix.
$\rho_{\text{p}} = 2650\ \text{kg/m}^3$	Particle density (SiO_2)
$\rho_{\text{A,norm}} = 1.293\ \text{kg/m}^3$	Air density at standard conditions
$p_{\text{amb}} = 1013.25\,\text{mbar}$	Ambient pressure

The sensor positions are shown in Figure 1. The names are equal to the column names in the measurement csv files in the data repository.

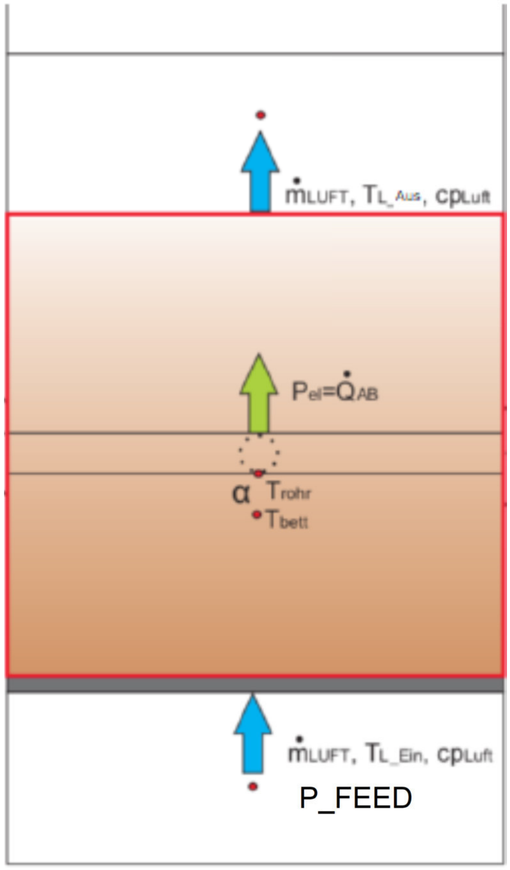


Figure 1: Sensor Positions

The feed pressure was measured in the case of the 87 µm experiments and is recorded as "P_FEED" in the respective csv files. After taking the mean values of feed pressure for all experiments, a linear regression analysis was used to determine the bed height (constant part of the pressure loss across both the distribution floor and the bed), which resulted in a constant pressure at the bed's bottom of 4335 Pa. Unfortunately, the feed pressure was not recorded in the 210 µm experiments, which is why it is assumed that the bed height was about the same in both types of experiments.

The volume flow of the fluidization air was measured with a rotameter, see equipment list in the data repository. Since the pressure of the supply air fluctuated between 1.5 and 2 barg, the volume flow measured with the rotameter was corrected to the one at these two pressures. A conversion tool provided by the supplier was used for this, which can be found in the data repository together with the necessary configuration files. The resulting volume flows are called "VdotAir15" at 1.5 barg and "VdotAir20" at 2 barg in the MATLAB script. The actual volume flow was then taken as the mean of these two volume flows.

Calculations

$p_A = p_{amb} + 4335\,\mathrm{Pa}$	Pressure of the fluidization air at the bottom of the bed, as explained above

$\rho_A = f(p_A, T_{BED1})$

Fluidization air density as a function of pressure and bed temperature based on the ideal gas equation

$$\dot{V} = \frac{\dot{V}_{Air1.5} + \dot{V}_{Air2}}{2} \cdot \frac{\rho_{A,norm}}{\rho_A}$$

Mean volume flow, as explained above, at actual conditions

$\eta_A = f(T_{BED1})$

Fluidization air dynamic viscosity as a function of bed temperature. Property function of dry air at ambient pressure according to VDI Heat Atlas[1].

$$\mathrm{Ar} = \frac{\rho_A d_p^3 (\rho_p - \rho_A) g}{\eta_A^2}$$

Archimedes number

$$\mathrm{Re} = \sqrt{C_1^2 + C_2 \mathrm{Ar}} - C_1$$

Reynolds number with $C_1 = 25.7$ and $C_2 = 0.0365$ according to Richardson [17]

$$w_{mf} = \mathrm{Re} \frac{\eta_A}{d_p \rho_A}$$

Minimum fluidization velocity

$\dot{V}_{mf} = w_{mf} l w$

Minimum fluidization volume flow

$$\mathrm{FG} = \frac{\dot{V}}{\dot{V}_{mf}}$$

Fluidization grade

$$T_{surf} = \frac{T_{PROBE1} + T_{PROBE2}}{2}$$

Tube surface temperature as mean of the two separate measurements

$$\alpha_{gross} = \frac{U I}{A(T_{surf} - T_{BED1})}$$

Gross heat transfer coefficient

$\dot{m}_A = \dot{V} \rho_A$

Fluidization air mass flow

$\dot{Q}_{loss} = \dot{m}_A (h(T_{Laus}) - h(T_{Lein}))$

Heat losses due to fluidization. Specific enthalpy of dry air at ambient pressure according to VDI Heat Atlas[2]

$$\alpha_{net} = \frac{U I - \dot{Q}_{loss}}{A(T_{surf} - T_{BED1})}$$

Net heat transfer coefficient

1 https://materials.springer.com/lb/docs/sm_nlb_978-3-540-77877-6_11
2 https://materials.springer.com/lb/docs/sm_nlb_978-3-540-77877-6_11

3 Measurement Uncertainty

3.1 Sensor Ranges

Table 1 shows the accuracies of all the different sensors and, if applicable, of their transmitters or transformers.

Value	Step	Accuracy Step	Base	Total Accuracy
T_{BED1}, T_{PROBE1}, T_{PROBE2}, T_{Lein}, T_{Laus}	Thermometer	$\pm(0.1+0.0017\frac{\lvert T\rvert}{°\mathrm{C}})°\mathrm{C}$	Actual	$\pm(0.6+0.0017\frac{\lvert T\rvert}{°\mathrm{C}})°\mathrm{C}$
	Transmitter	$\pm 0.5°\mathrm{C}$	Actual	
$\dot{V}_{\mathrm{Air1.5}}$, $\dot{V}_{\mathrm{Air2}}$	Rotameter		Actual	$\dot{V} < 10\,\mathrm{Nm^3/h}:\ \pm 1\%\frac{10\,\mathrm{Nm^3/h}}{\dot{V}}$ $\dot{V} \geq 10\,\mathrm{Nm^3/h}:\ \pm 1\%$
U	Power Supply		Actual	$\pm(0.05\%+20\,\mathrm{mV})$
I	Power Supply		Actual	$\pm(0.2\%+20\,\mathrm{mA})$

Table 1: Accuracies of individual sensors and their intermediate steps

The "Base" column denotes whether the accuracy is based on the currently measured value ("Actual") or the entire range of possible values ("Range"). The accuracies of all equipment are documented in the euipment list and data sheets in the data repository.

Apart from the calculation of value ranges, all calculations are performed the same way as described in the previous section.

Calculations

Temperature ranges

$\Delta T = f(T) = 0.6 + 0.0017 \cdot \lvert T \rvert$	Observational error of all temperature values. T in °C
$T_{\mathrm{BED1min}} = T_{\mathrm{BED1}} - \Delta T(T_{\mathrm{BED1}})$	Minimum value of T_{BED1}
$T_{\mathrm{BED1max}} = T_{\mathrm{BED1}} + \Delta T(T_{\mathrm{BED1}})$	Maximum value of T_{BED1}
$\vdots$	Repeat for all temperature measurements

Volume flow ranges. Observational error of all volume flow values:

$$\Delta \dot{V}_{\mathrm{Air}} = f(\dot{V}_{\mathrm{Air}}, \dot{V}) = \left\{ \begin{array}{ll} \dot{V} < 10\,\mathrm{Nm^3/h}: & \frac{\dot{V}_{\mathrm{Air}}}{100} \frac{10\,\mathrm{Nm^3/h}}{\dot{V}} \\ \dot{V} \geq 10\,\mathrm{Nm^3/h}: & \frac{\dot{V}_{\mathrm{Air}}}{100} \end{array} \right\}$$

$\dot{V}_{\text{Air1.5min}} = \dot{V}_{\text{Air1.5}} - \Delta \dot{V}_{\text{Air}}\left(\dot{V}_{\text{Air1.5}}\right)$ Minimum value of $\dot{V}_{\text{Air1.5}}$

$\dot{V}_{\text{Air1.5max}} = \dot{V}_{\text{Air1.5}} + \Delta \dot{V}_{\text{Air}}\left(\dot{V}_{\text{Air1.5}}\right)$ Maximum value of $\dot{V}_{\text{Air1.5}}$

$\vdots$ Repeat for $\dot{V}_{\text{Air2}}$

Voltage ranges

$\Delta U = f(U) = 0.05\% \cdot U + 20\,\text{mV}$ Observational error of voltage values

$U_{\min} = U - \Delta U(U)$ Minimum value of U

$U_{\max} = U + \Delta U(U)$

Current ranges

$\Delta I = f(I) = 0.2\% \cdot I + 20\,\text{mA}$ Observational error of current values

$I_{\min} = I - \Delta I(I)$ Minimum value of I

$I_{\max} = I + \Delta I(I)$ Maximum value of I

3.2 Ranges in Degree of Fluidization

$\rho_{\mathrm{Amin}} = f(p_{\mathrm{A}}, T_{\mathrm{BED1max}})$ Minimum fluidization air density

$\rho_{\mathrm{Amax}} = f(p_{\mathrm{A}}, T_{\mathrm{BED1min}})$ Maximum fluidization air density

$$\dot{V}_{\mathrm{min}} = \frac{\dot{V}_{\mathrm{Air1.5min}} + \dot{V}_{\mathrm{Air2min}}}{2} \cdot \frac{\rho_{\mathrm{A,norm}}}{\rho_{\mathrm{Amax}}}$$ Minimum volume flow

$$\dot{V}_{\mathrm{max}} = \frac{\dot{V}_{\mathrm{Air1.5max}} + \dot{V}_{\mathrm{Air2max}}}{2} \cdot \frac{\rho_{\mathrm{A,norm}}}{\rho_{\mathrm{Amin}}}$$ Maximum volume flow

The following calculations of the air dynamic viscosity, the Archimedes number, and the Reynolds number are all required to calculate the minimun fluidization velocity. It can be easily shown that the minimum fluidization velocity decreases with increasing fluidization air temperature when all other parameters (particle diameter and particle density) remain the same. Therefore, the Archimedes and Reynolds numbers for the minimal minimum fluidization veloctiy are all calculated with physical properties at maximum temperatures and vice versa.

$\eta_{\mathrm{Amin}} = f(T_{\mathrm{BED1max}})$ Minimum fluidization air dynamic viscosity

$\eta_{\mathrm{Amax}} = f(T_{\mathrm{BED1min}})$ Maximum fluidization air dynamic viscosity

$$\mathrm{Ar}_{\mathrm{min}} = \frac{\rho_{\mathrm{Amin}} d_{\mathrm{p}}^{3} (\rho_{\mathrm{p}} - \rho_{\mathrm{Amin}}) g}{\eta_{\mathrm{Amin}}^{2}}$$ Minimum Archimedes number

$$\mathrm{Ar}_{\mathrm{max}} = \frac{\rho_{\mathrm{Amax}} d_{\mathrm{p}}^{3} (\rho_{\mathrm{p}} - \rho_{\mathrm{Amax}}) g}{\eta_{\mathrm{Amax}}^{2}}$$ Maximum Archimedes number

$\mathrm{Re}_{\mathrm{min}} = \sqrt{C_1^2 + C_2 \mathrm{Ar}_{\mathrm{min}}} - C_1$ Minimum Reynolds number

$\mathrm{Re}_{\mathrm{max}} = \sqrt{C_1^2 + C_2 \mathrm{Ar}_{\mathrm{max}}} - C_1$ Maximum Reynolds number

$$w_{\mathrm{mfMin}} = \mathrm{Re}_{\mathrm{min}} \frac{\eta_{\mathrm{Amin}}}{d_{\mathrm{p}} \rho_{\mathrm{Amin}}}$$ Minimal minimum fluidization velocity

$$w_{\mathrm{mfMax}} = \mathrm{Re}_{\mathrm{max}} \frac{\eta_{\mathrm{Amax}}}{d_{\mathrm{p}} \rho_{\mathrm{Amin}}}$$ Maximal minimum fluidization velocity

$\dot{V}_{\mathrm{mfMin}} = w_{\mathrm{mfMin}}\, l\, w$ Minimal minimum fluidization volume flow

$\dot{V}_{\mathrm{mfMax}} = w_{\mathrm{mfMax}}\, l\, w$ Maximal minimum fluidization volume flow

$$FG_{min} = \frac{\dot{V}_{min}}{\dot{V}_{mfMax}}$$

Minimum fluidization grade

$$FG_{max} = \frac{\dot{V}_{max}}{\dot{V}_{mfMin}}$$

Maximum fluidization grade

3.3 Ranges in Heat Transfer Coefficients

$$T_{surfMin} = \frac{T_{PROBE1min} + T_{PROBE2min}}{2}$$

Minimum tube surface temperature

$$T_{surfMax} = \frac{T_{PROBE1max} + T_{PROBE2max}}{2}$$

Maximum tube surface temperature

$$\alpha_{grossMin} = \frac{U_{min} I_{min}}{A(T_{surfMax} - T_{BED1min})}$$

Minimum gross heat transfer coefficient

$$\alpha_{grossMax} = \frac{U_{max} I_{max}}{A(T_{surfMin} - T_{BED1max})}$$

Maximum gross heat transfer coefficient

$$\dot{m}_{Amin} = \frac{\dot{V}_{Air1.5min} + \dot{V}_{Air2min}}{2} \cdot \rho_{A,norm}$$

Minimum fluidization air mass flow

$$\dot{m}_{Amax} = \frac{\dot{V}_{Air1.5max} + \dot{V}_{Air2max}}{2} \cdot \rho_{A,norm}$$

Maximum fluidization air mass flow

$$\dot{Q}_{lossMin} = \dot{m}_{Amin}\left(h(T_{LausMin}) - h(T_{LeinMax})\right)$$

Minimum heat losses due to fluidization

$$\dot{Q}_{lossMax} = \dot{m}_{Amax}\left(h(T_{LausMax}) - h(T_{LeinMin})\right)$$

Maximum heat losses due to fluidization

$$\alpha_{netMin} = \frac{U_{min} I_{min} - \dot{Q}_{lossMax}}{A(T_{surfMax} - T_{BED1min})}$$

Minimum net heat transfer coefficient

$$\alpha_{netMax} = \frac{U_{max} I_{max} - \dot{Q}_{lossMin}}{A(T_{surfMin} - T_{BED1max})}$$

Maximum net heat transfer coefficient

The results of all the relative uncertainties can be seen in the form of graphs in the data repository.

4 Appendix

MASTERSIZER 2000

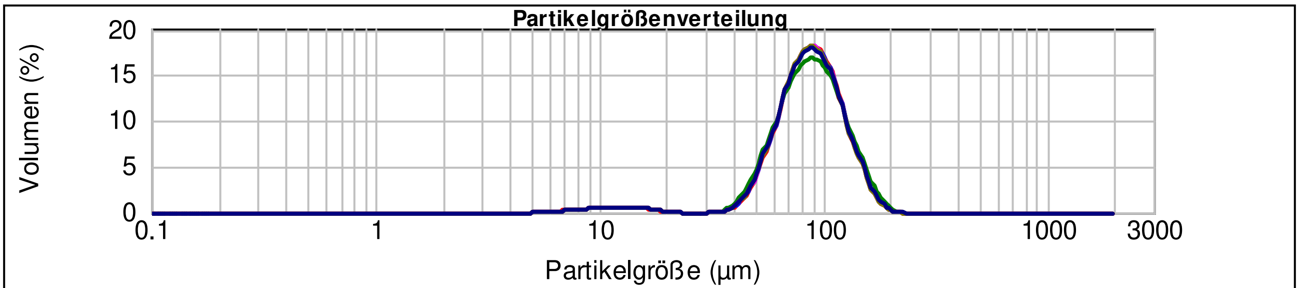
Analyse Report

Probenname:	SiO2 Wärmeträgermedium -	**SOP**	SiO2 Thermodyn using	**Gemessen:**	Tuesday, October 02,
Probenherkunft:	Fabrik = Thermodyn	**Operator:**	gmausch	**Berechnet:**	Tuesday, October 02,
Probenreferenz:	A1			**Datenursprung:**	Gemittelt

Probenmaterial:	Silica 1.45	**Dispergiermodul:**	Scirocco 2000 (B)	**Abschattung:**	7.79 %
Partikel RI:	1.450 **Absorption:** 0.1	**Analysemodell:**	Universal		
Dispergierfluid:		**Meßbereich:**	0.020 to 2000.0... um	**Fit(gewichtet):**	0.854 %
Fluid RI:	1.000	**Emulatio...**	Aus		

Konzentration:	0.0179 %Vol	**Vol. Mittelwert D[4,3]:**	89.688 um	**Spezifische Oberfläche:**	0.0881 m²/g
Breite :	0.876	**Gleichförmigkeit:**	0.284	**D[3,2]:**	68.067 um
Verteilungsart:	Volumen				

d(0.1): 54.853 um **d(0.5): 87.141** um d(0.9): 131.225 um



SiO2 Wärmeträgermedium, Tuesday, October 02, 2018 10:32:17 AM
SiO2 Wärmeträgermedium, Tuesday, October 02, 2018 10:37:09 AM
SiO2 Wärmeträgermedium, Tuesday, October 02, 2018 10:37:27 AM
SiO2 Wärmeträgermedium, Tuesday, October 02, 2018 10:37:44 AM
SiO2 Wärmeträgermedium, Tuesday, October 02, 2018 10:38:02 AM
SiO2 Wärmeträgermedium, Tuesday, October 02, 2018 10:38:20 AM
SiO2 Wärmeträgermedium - Mittelwert, Tuesday, October 02, 2018 10:37:09 AM

Größen-	Häufigkeit (%)
0.020	0.00
0.025	0.00
0.032	0.00
0.040	0.00
0.050	0.00
0.063	0.00
0.080	0.00
0.100	0.00
0.126	0.00
0.159	

Größen-	Häufigkeit (%)
0.159	0.00
0.200	0.00
0.252	0.00
0.317	0.00
0.399	0.00
0.502	0.00
0.632	0.00
0.796	0.00
1.002	0.00
1.262	

Größen-	Häufigkeit (%)
1.262	0.00
1.589	0.00
2.000	0.00
2.518	0.00
3.170	0.00
3.991	0.00
5.024	0.11
6.325	0.36
7.962	0.67
10.024	

Größen-	Häufigkeit (%)
10.024	0.92
12.619	0.92
15.887	0.50
20.000	0.03
25.179	0.00
31.698	0.29
39.905	3.05
50.238	10.97
63.246	21.77
79.621	

Größen-	Häufigkeit (%)
79.621	26.70
100.237	21.35
126.191	10.07
158.866	2.27
200.000	0.04
251.785	0.00
316.979	0.00
399.052	0.00
502.377	0.00
632.456	

Größen-	Häufigkeit (%)
632.456	0.00
796.214	0.00
1002.374	0.00
1261.915	0.00
1588.656	0.00
2000.000	

Kommentar:

BCS221

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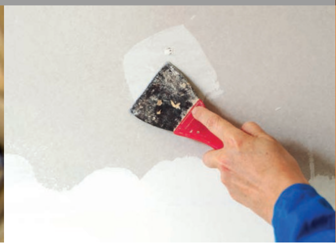

Chemische Analyse | Chemical analysis

Fe_2O_3	< 0,2 %
Al_2O_3	< 0,2 %
TiO_2	< 0,2 %
SiO_2	> 99,1 %

Physikalische Kenndaten | Physical characteristics

Mittlere Körnung | Medium grain size	0,21 mm
AFS Kennzahl | AFS number	64
Theoretische spezifische Oberfläche | Theoretic specific surface area	112 cm^2/g
Gleichmäßigkeitsgrad | Uniformity ratio	77 %
Glühverlust | Loss on ignition	< 0,2 %
Sinterbeginn | Sintering point	> 1550 °C
Schüttdichte feuergetrocknet | Bulk density fire dried	1,37 to/m^3

Korngrößenverteilung | Grain size distribution

Maschenweite | Mesh Size (mm)	Rückstand | Residue (%)	Summe | Sum (%)	Toleranzbereich | Tolerance range (%)
> 0,710	0,0		
0,500–0,710	0,1	100,0	0–0,5
0,355–0,500	1,3	99,9	0–4
0,250–0,355	12,0	98,6	6–16
0,180–0,250	64,0	86,6	53–72
0,125–0,180	21,0	22,6	15–30
0,090–0,125	1,3	1,6	0–3
0,063–0,090	0,2	0,3	0–0,5
0,000–0,063	0,1	0,1	0–0,2

Die angegebenen Daten stellen Jahresdurchschnittswerte dar, eine Verbindlichkeit kann daraus nicht abgeleitet werden.

The shown data represent annual averages, a liability can not be deduced.

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