Methodology

of

TRINI 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_TRINI" in the software repository and are based on data in the data repository (all .csv-files starting with TRINI). 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 Constants

$l_{\mathrm{heated}} = 0.216\ \mathrm{m}$	Heated tube length
$d = 25\mathrm{e}\text{-}3\ \mathrm{m}$	Tube diameter
$A = d\,\pi\,l_{\mathrm{heated}}$	Heated tube area
$A_{\mathrm{FB,in}} = A_{\mathrm{FB,out}} = 0.2 \cdot 0.203\ \mathrm{m}^2$	Fluidized bed grid area, inlet / outlet chamber
$A_{\mathrm{FB,main}} = 0.2 \cdot 0.597\ \mathrm{m}^2$	Fluidized bed grid area, main chamber
$d_{\mathrm{p}} = 146\mathrm{e}\text{-}6\ \mathrm{m}$	Mean particle diameter. The data sheet is in the appendix.
$\rho_{\mathrm{p}} = 2650\ \mathrm{kg/m^3}$	Particle density (SiO_2)
$\eta_{\mathrm{A}} = 18.107811\mathrm{e}\text{-}6\ \mathrm{Pa\,s}$	Dynamic viscosity of air at 20°C and ambient pressure, according to VDI Heat Atlas[1]
$R_{\mathrm{A}} = 287.0533\ \mathrm{J/kg\,K}$	Ideal gas constant of air
$p_{\mathrm{amb}} = 101325\ \mathrm{Pa}$	Ambient pressure

The following constants refer to the sinter floor. The data sheet is in the appendix; the used type is “SIKA-B 20”.

$\alpha = 10\mathrm{e}\text{-}12\ \mathrm{m}^2$	Viscosity coefficient
$\beta = 83\mathrm{e}\text{-}12\ \mathrm{m}$	Inertia coefficient
$s = 20\mathrm{e}\text{-}3\ \mathrm{m}$	Floor thickness

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

3 Fluidization Air Flows

The fluidization air flow was measured at a common location before being distributed to the different fluidization chambers. In order to correctly calculate the heat losses caused by the fluidization, the air distribution has to be calculated first. This was done by using the pressure differences across the different sinter floors to estimate the volume flow through them. Figure 1 shows the relevant parameters for the calculations and where they were measured.

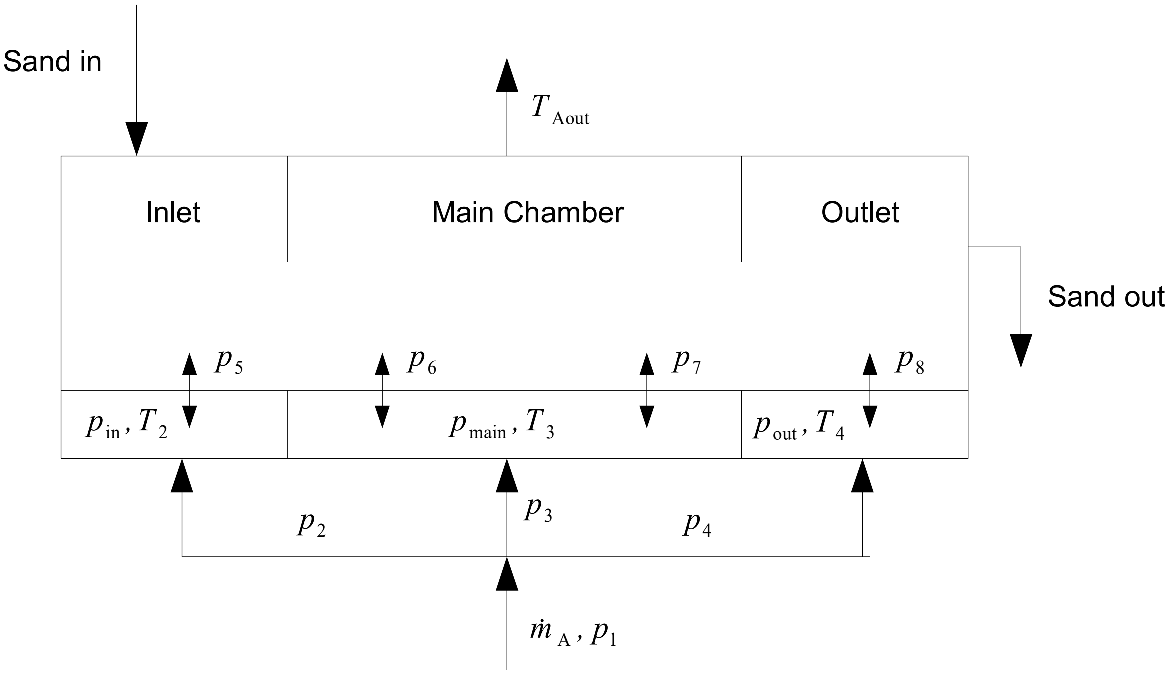

Figure 1: Measurements for the calculation of flow distribution

The variable names refer to the ones in the measurement Excel file.

p_1	Pressure difference of air to ambient pressure at the mass flow measurement position
p_2	Pressure difference between mass flow measurement position and inlet chamber
p_3	Pressure difference between mass flow measurement position and main chamber
p_4	Pressure difference between mass flow measurement position and outnlet chamber
p_5	Pressure difference across sinter floor, inlet chamber
p_6	First pressure difference across sinter floor, main chamber
p_7	Second pressure difference across sinter floor, main chamber
p_8	Pressure difference across sinter floor, outlet chamber
T_2	Temperature in inlet chamber
T_3	Temperature in main chamber
T_4	Temperature in outlet chamber

Calculations

$p_{in} = p_1 - p_2 + p_{amb}$ Absolute pressure in inlet chamber

$p_{main} = p_1 - p_3 + p_{amb}$ Absolute pressure in main chamber

$p_{out} = p_1 - p_4 + p_{amb}$ Absolute pressure in outlet chamber

$\rho_{in} = \frac{p_{in}}{R_A T_2}$ Air density in inlet chamber

$\rho_{main} = \frac{p_{main}}{R_A T_3}$ Air density in main chamber

$\rho_{out} = \frac{p_{out}}{R_A T_4}$ Air density in outlet chamber

According to the sinter floor data sheet in the appendix, the Volume flow $\dot{V}$ can be calculated as:

$$\Delta p = \frac{\dot{V} s}{A}\left(\frac{\eta_A}{\alpha} + \frac{\rho \dot{V}}{\beta A}\right)$$

Where Δp is the pressure difference across the sinter floor, A is the sinter floor area, ρ is the air density and s , η_A , α and β are constants described in the previous section. The volume flow can then be calculated as:

$$\lambda = \frac{\eta_A \beta A}{\rho \alpha}$$

$$\dot{V} = -\frac{\lambda}{2} + \sqrt{\left(\frac{\lambda}{2}\right)^2 + \frac{\beta A^2 \Delta p}{\rho s}}$$

This can be used to calculate:

$\dot{V}_{in,est} = f(\rho_{in}, A_{FB,in}, p_5)$ Estimated air volume flow in input chamber

$\dot{V}_{main,est} = f(\rho_{main}, A_{FB,main}, \frac{p_6 + p_7}{2})$ Estimated air volume flow in main chamber

$\dot{V}_{out,est} = f(\rho_{out}, A_{FB,out}, p_8)$ Estimated air volume flow in output chamber

$\dot{m}_{A,in,est} = \dot{V}_{in,est} \rho_{in}$ Estimated air mass flow in input chamber

$\dot{m}_{A,main,est} = \dot{V}_{main,est} \rho_{main}$ Estimated air mass flow in main chamber

$\dot{m}_{A,out,est} = \dot{V}_{out,est} \rho_{out}$ Estimated air mass flow in output chamber

$\dot{m}_{A,est} = \dot{m}_{A,in,est} + \dot{m}_{A,main,est} + \dot{m}_{A,out,est}$ Estimated total air mass flow

$\dot{m}_A$ Actual (measured) total air mass flow

$$\dot{m}_{\mathrm{A,in}} = \dot{m}_{\mathrm{A,in,est}} \frac{\dot{m}_{\mathrm{A}}}{\dot{m}_{\mathrm{A,est}}}$$

Corrected mass flow in inlet chamber

$$\dot{m}_{\mathrm{A,main}} = \dot{m}_{\mathrm{A,main,est}} \frac{\dot{m}_{\mathrm{A}}}{\dot{m}_{\mathrm{A,est}}}$$

Corrected mass flow in main chamber

$$\dot{m}_{\mathrm{A,out}} = \dot{m}_{\mathrm{A,out,est}} \frac{\dot{m}_{\mathrm{A}}}{\dot{m}_{\mathrm{A,est}}}$$

Corrected mass flow in outlet chamber

The degree of fluidization is then calculated as:

$$p_{\mathrm{A}} = p_{\mathrm{main}} - \frac{p_6 + p_7}{2}$$

Mean fluidization air pressure

$$T_{\mathrm{A,in}} = T_3$$

$$T_{\mathrm{A}} = \frac{T_{\mathrm{Ain}} + T_{\mathrm{Aout}}}{2}$$

Mean fluidization air temperature

$$\rho_{\mathrm{A}} = f(p_{\mathrm{A}}, T_{\mathrm{A}})$$

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

$$\eta_{\mathrm{A}} = f(T_{\mathrm{A}})$$

Fluidization air dynamic viscosity as a function of bed temperature. Property function of dry air at ambient pressure according to VDI Heat Atlas[2].

$$\mathrm{Ar} = \frac{\rho_{\mathrm{A}} d_{\mathrm{p}}^3 (\rho_{\mathrm{p}} - \rho_{\mathrm{A}}) g}{\eta_{\mathrm{A}}^2}$$

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]

$$w_{\mathrm{mf}} = \mathrm{Re} \frac{\eta_{\mathrm{A}}}{d_{\mathrm{p}} \rho_{\mathrm{A}}}$$

Minimum fluidization velocity

$$\dot{V}_{\mathrm{mf,main}} = w_{\mathrm{mf}} A_{\mathrm{FB,main}}$$

Minimum fluidization volume flow in main chamber

$$\mathrm{FG} = \frac{\dot{m}_{\mathrm{A,main}}}{\rho_{\mathrm{A}} \dot{V}_{\mathrm{mf,main}}}$$

Fluidization grade in main chamber

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

4 Plain Tube Calculations

A sketch of the plain tube setup including some sensor positions is shown in Figure 2. The names are equal to the column names in the measurement csv file.

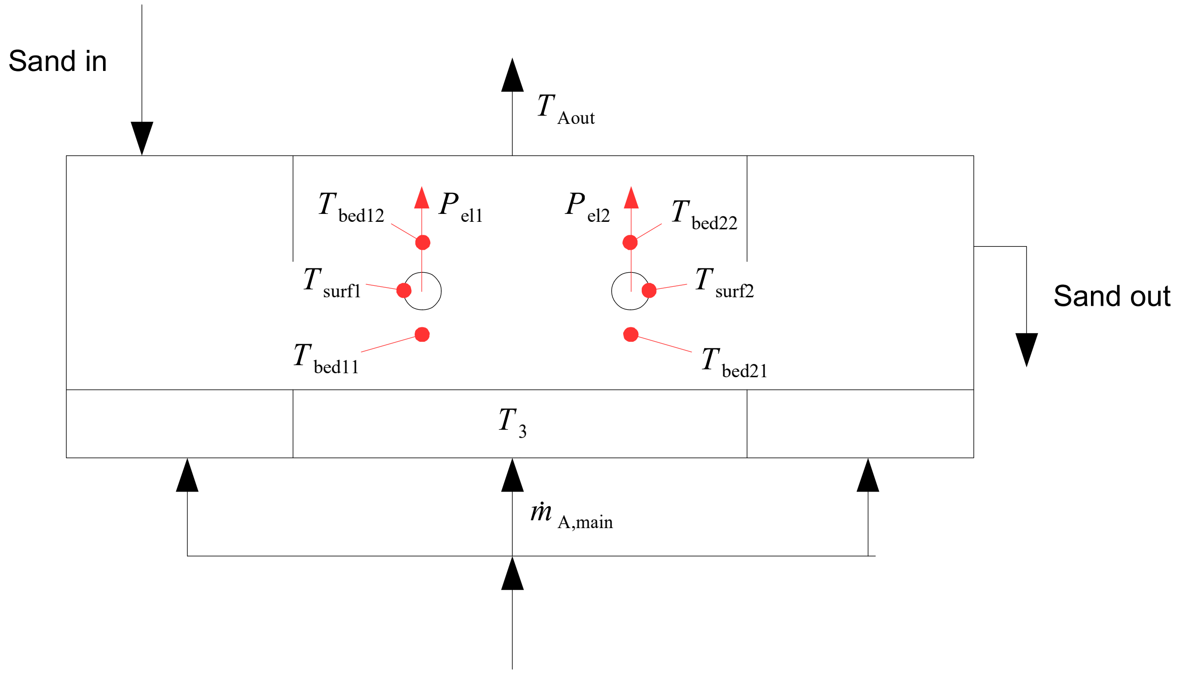

Figure 2: Measurement setup and sensor positions in the plain tube configuration

Calculations

$$T_{bed1} = \frac{T_{bed11} + T_{bed12}}{2}$$ Mean bed temperature at first probe

$$T_{bed2} = \frac{T_{bed21} + T_{bed22}}{2}$$ Mean bed temperature at second probe

$$\alpha_{gross1} = \frac{U_1 I_1 \cos(\varphi_1)}{A(T_{surf1} - T_{bed1})}$$ Gross heat transfer coefficient, first probe

$$\alpha_{gross2} = \frac{U_2 I_2 \cos(\varphi_2)}{A(T_{surf2} - T_{bed1})}$$ Gross heat transfer coefficient, second probe

$$\alpha_{gross,mean} = \frac{\alpha_{gross1} + \alpha_{gross2}}{2}$$ Gross heat transfer coefficient, mean

$$\dot{Q}_{loss} = \dot{m}_{A,main}\left(h(T_{Aout}) - h(T_{Ain})\right)$$ Heat losses due to fluidization. Specific enthalpy of dry air at ambient pressure according to VDI Heat Atlas[3]

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

$$\alpha_{\mathrm{net1}} = \frac{U_1 I_1 \cos(\varphi_1) - \dot{Q}_{\mathrm{loss}}/2}{A(T_{\mathrm{surf1}} - T_{\mathrm{bed1}})}$$

Net heat transfer coefficient, first probe

$$\alpha_{\mathrm{net2}} = \frac{U_2 I_2 \cos(\varphi_2) - \dot{Q}_{\mathrm{loss}}/2}{A(T_{\mathrm{surf2}} - T_{\mathrm{bed2}})}$$

Net heat transfer coefficient, second probe

$$\alpha_{\mathrm{net,mean}} = \frac{\alpha_{\mathrm{net1}} + \alpha_{\mathrm{net2}}}{2}$$

Net heat transfer coefficient, mean

5 Finned Tube Calculations

A sketch of the finned tube setup including some sensor positions is shown in Figure 3. The names are equal to the column names in the measurement Excel file.

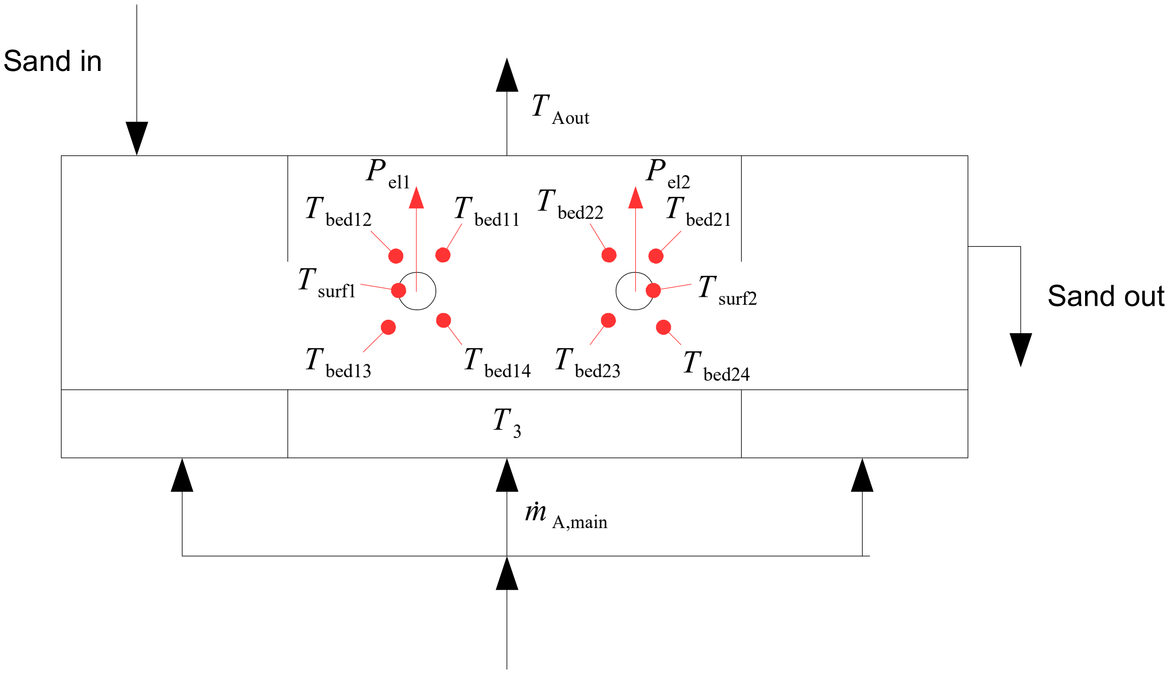

Figure 3: Measurement setup and sensor positions in the finned tube configuration

Calculations

$$T_{\text{bed1}} = \frac{T_{\text{bed11}} + T_{\text{bed12}} + T_{\text{bed13}} + T_{\text{bed14}}}{2}$$

Mean bed temperature at first probe

$$T_{\text{bed2}} = \frac{T_{\text{bed21}} + T_{\text{bed22}} + T_{\text{bed23}} + T_{\text{bed24}}}{2}$$

Mean bed temperature at second probe

$$\alpha_{\text{gross1}} = \frac{U_1 I_1 \cos(\varphi_1)}{A(T_{\text{surf1}} - T_{\text{bed1}})}$$

Gross heat transfer coefficient, first probe

$$\alpha_{\text{gross2}} = \frac{U_2 I_2 \cos(\varphi_2)}{A(T_{\text{surf2}} - T_{\text{bed1}})}$$

Gross heat transfer coefficient, second probe

$$\alpha_{\text{gross,mean}} = \frac{\alpha_{\text{gross1}} + \alpha_{\text{gross2}}}{2}$$

Gross heat transfer coefficient, mean

$$\dot{Q}_{\text{loss}} = \dot{m}_{\text{A,main}} \left(h(T_{\text{Aout}}) - h(T_{\text{Ain}}) \right)$$

Heat losses due to fluidization. Specific enthalpy of dry air at ambient pressure according to VDI Heat Atlas[4]

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

$$\alpha_{net1} = \frac{U_1 I_1 \cos(\varphi_1) - \dot{Q}_{loss}/2}{A(T_{surf1} - T_{bed1})}$$ Net heat transfer coefficient, first probe

$$\alpha_{net2} = \frac{U_2 I_2 \cos(\varphi_2) - \dot{Q}_{loss}/2}{A(T_{surf2} - T_{bed2})}$$ Net heat transfer coefficient, second probe

$$\alpha_{net,mean} = \frac{\alpha_{net1} + \alpha_{net2}}{2}$$ Net heat transfer coefficient, mean

6 Measurement Uncertainty

6.1 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_2, T_3, T_4, T_{bed11}, T_{bed12}, T_{bed13}, T_{bed14}, T_{bed21}, T_{bed22}, T_{bed23}, T_{bed24}, T_{surf1}, T_{surf2}	Sensor	$\pm\left(0.15+0.002\frac{\lvert T\rvert}{°\text{C}}\right)°\text{C}$	Actual	See description
	Transmitter	Offset: $\pm 0{,}0015\,\%\,\Omega$	Range	
		Gain: $\pm 0{,}0059\,\%\,\Omega$	Actual	
p_1, p_4, p_5, p_6, p_7, p_8	Sensor	$\pm 0.5\%$	Range	$X20AI4632(\pm 0.5\,\%\,p_{\text{Range}})$
	Transmitter	X20AI4632		
p_2, p_3	Sensor	$\pm 0.8\%$	Range	$X20AI4632(\pm 0.8\,\%\,p_{\text{Range}})$
	Transmitter	X20AI4632		
$\dot{m}_{\text{A}}$	Sensor	$0\,\% \leq \dot{m}_{\text{A}} \leq 20\,\%: \pm 0.8\,\%$	Range	See description
		$20\,\% < \dot{m}_{\text{A}} \leq 100\,\%: \pm 4\,\%$	Actual	
	Transformer	$\pm 0.05\%$ or $\pm 10\,\mu\text{A}$	Range	
	Transmitter	X20AI4632		
X20AI4632	Transmitter	Offset: $\pm 0.02\,\%$	Range	See description
		Gain: $\pm 0.08\%$	Actual	
U	Transmitter		Actual	$\pm 0.65\%$
I	Transformer	$\pm 1\,\%$	Actual	$\pm 1.707\,\%$
	Measurement	$\pm 0.7\%$	Actual	
φ	Transformer	$\pm 60'$	Actual	$\pm(0.5\,\%+60')$
	Measurement	$\pm 0.5\%$	Actual	

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.

The transmitter X20AI432 was used to measure the current signals (4 – 20 mA) of the pressure and mass flow sensors. The calculation of its accuracy is described separately below.

The pressure sensors have different measurement ranges shown in Table 2.

Value	MRB (Pa)	MRE (Pa)
p_1	0	50 000
p_2 , p_3	0	5 000
p_4 , p_5 , p_6 , p_7 , p_8	0	25 000

Table 2: Measurement ranges of pressure sensors

MRB stands for Measurement Range Beginning, MRE for Measurement Range End.

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

Calculations

The pressure and mass flow measurements are transformed into 4 – 20 mA current signals, which are then measured by a current measurement module of the process control system (X20AI4632, see equipment list) before being converted into a digital signal. The inaccuracy of the current measurement module can be put in two functions, describing the possible minimum value min_{CM} and maximum value max_{CM} of a signal x with an upper measurement range MRE and lower measurement range MRB :

$$min_{\mathrm{CM}} = f(x, MRB, MRE) =$$
$$\left(\left(\frac{x}{MRE - MRB} \cdot 16\,\mathrm{mA} + 4\,\mathrm{mA}\right)(1 - 0.08\,\%) - 0.02\,\%\,20\,\mathrm{mA} - 4\,\mathrm{mA}\right)\left(\frac{MRE - MRB}{16\,\mathrm{mA}}\right)$$

$$max_{\mathrm{CM}} = f(x, MRB, MRE) =$$
$$\left(\left(\frac{x}{MRE - MRB} \cdot 16\,\mathrm{mA} + 4\,\mathrm{mA}\right)(1 + 0.08\,\%) + 0.02\,\%\,20\,\mathrm{mA} - 4\,\mathrm{mA}\right)\left(\frac{MRE - MRB}{16\,\mathrm{mA}}\right)$$

Mass flow ranges. Observational error of all mass flow values:

$$\Delta \dot{m}_{\mathrm{A}} = f(\dot{m}_{\mathrm{A}}) = \begin{Bmatrix} \dot{m}_{\mathrm{A}} < 406\,\mathrm{kg/h}: & 0.8\,\%\,2300\,\mathrm{kg/h} = 3.248\,\mathrm{kg/h} \\ \dot{m}_{\mathrm{A}} \geq 406\,\mathrm{kg/h}: & 4\,\%\,\dot{m}_{\mathrm{A}} \end{Bmatrix}$$

$MRB_{\dot{m}} = 0\,\mathrm{kg/s}$	Measurement Range Beginning of sensor
$MRE_{\dot{m}} = 0.5\,\mathrm{kg/s}$	Measurement Range End of sensor
$bias_{\mathrm{Tr}} = \frac{10\,\mu\mathrm{A}}{16\,\mathrm{mA}}(MRE_{\dot{m}} - MRB_{\dot{m}}) = 3.125\mathrm{e}{-4}\,\mathrm{kg/s}$	Bias of mass flowmeter signal transformer
$\dot{m}_{\mathrm{AminTr}} = \dot{m}_{\mathrm{A}} - \Delta \dot{m}_{\mathrm{A}}(\dot{m}_{\mathrm{A}}) - bias_{\mathrm{Tr}}$	Minimum mass flow after flowmeter transformer
$\dot{m}_{\mathrm{AmaxTr}} = \dot{m}_{\mathrm{A}} + \Delta \dot{m}_{\mathrm{A}}(\dot{m}_{\mathrm{A}}) + bias_{\mathrm{Tr}}$	Maximum mass flow after flowmeter transformer
$\dot{m}_{\mathrm{Amin}} = min_{\mathrm{CM}}(\dot{m}_{\mathrm{AminTr}}, MRB_{\dot{m}}, MRE_{\dot{m}})$	Minimum mass flow
$\dot{m}_{\mathrm{Amax}} = max_{\mathrm{CM}}(\dot{m}_{\mathrm{AmaxTr}}, MRB_{\dot{m}}, MRE_{\dot{m}})$	Maximum mass flow

Pressure ranges

$bias_{\mathrm{p}} = \begin{cases} p_1, p_4 - p_8: & 0.5\%(MRE - MRB) \\ p_2, p_3: & 0.8\%(MRE - MRB) \end{cases}$	Bias of pressure measurements. MRB and MRE according to table 2.

Maximum and minimum values of pressure:

$$p_{1\mathrm{min}} = min_{\mathrm{CM}}(p_1 - bias_{\mathrm{p}}(p_1), MRB(p_1), MRE(p_1))$$

$$p_{1\mathrm{max}} = max_{\mathrm{CM}}(p_1 + bias_{\mathrm{p}}(p_1), MRB(p_1), MRE(p_1))$$

$\vdots$	Repeat for all pressure measurements

Temperature ranges

$\Delta T = f(T) = 0.15 + 0.002 \cdot \lvert T \rvert$	Observational error of all temperature values. T in °C
$T_{2\mathrm{sensorMin}} = T_2 - \Delta T(T_2)$	Minimum sensor value of T_2
$T_{2\mathrm{sensorMax}} = T_2 + \Delta T(T_2)$	Maximum sensor value of T_2
$R = f(T) = 100\,\Omega(1 + 3.9083\mathrm{e}\text{-}3\,T - 5.775\mathrm{e}\text{-}7\,T^2)$	Resistance of PT100 sensor at temperature T. Constants according to EN 60751
$gain_{\mathrm{T}} = 0.0059\,\%$	Gain of temperature transmitter, see table 1
$R_{2\mathrm{min}} = R(T_{2\mathrm{sensorMin}})(1 - gain_{\mathrm{T}})$	Minimum resistance of temperature sensor
$R_{2\mathrm{max}} = R(T_{2\mathrm{sensorMax}})(1 + gain_{\mathrm{T}})$	Maximum resistance of temperature sensor

Offset of temperature transmitter (see table 1), based on the resistance measurement range of the transmitter (0.5 – 390 Ω), its temperature measurement range (-200 – 850°C) and the corresponding resistance values of a PT100 sensor, according to EN 60751 and the transmitter data sheet:

$$offset_{\mathrm{T}} = 0.0015\mathrm{e}\text{-}2 * (390 - 0.5)/(390.48 - 18.52) * (850 + 200)$$

$T_{2\mathrm{min}} = R^{-1}(R_{2\mathrm{min}}) - offset_{\mathrm{T}}$	Minimum value of T_2
$T_{2\mathrm{max}} = R^{-1}(R_{2\mathrm{max}}) + offset_{\mathrm{T}}$	Maximum value of T_2
$\vdots$	Repeat for all temperature measurements

Voltage ranges

$\Delta U = f(U) = 0.05\% \cdot U + 20\,\mathrm{mV}$	Observational error of voltage values
$U_{\mathrm{min}} = U - \Delta U(U)$	Minimum value of U
$U_{\mathrm{max}} = U + \Delta U(U)$	

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

Phase angle ranges

$\varphi_{\min} = (\varphi - 1°)(1 - 0.5\%)$ Minimum value of φ

$\varphi_{\max} = (\varphi + 1°)(1 + 0.5\%)$ Maximum value of φ

6.2 Ranges in Degree of Fluidization

$p_{\mathrm{inMin}} = p_{1\mathrm{min}} - p_{2\mathrm{max}} + p_{\mathrm{amb}}$	Minimum inlet chamber air pressure
$p_{\mathrm{inMax}} = p_{1\mathrm{max}} - p_{2\mathrm{min}} + p_{\mathrm{amb}}$	Maximum inlet chamber air pressure
$p_{\mathrm{mainMin}} = p_{1\mathrm{min}} - p_{3\mathrm{max}} + p_{\mathrm{amb}}$	Minimum main chamber air pressure
$p_{\mathrm{mainMax}} = p_{1\mathrm{max}} - p_{3\mathrm{min}} + p_{\mathrm{amb}}$	Maximum main chamber air pressure
$p_{\mathrm{outMin}} = p_{1\mathrm{min}} - p_{4\mathrm{max}} + p_{\mathrm{amb}}$	Minimum outlet chamber air pressure
$p_{\mathrm{outMax}} = p_{1\mathrm{max}} - p_{4\mathrm{min}} + p_{\mathrm{amb}}$	Maximum outlet chamber air pressure
$\rho_{\mathrm{inMin}} = \frac{p_{\mathrm{inMin}}}{R_{\mathrm{A}} T_{2\mathrm{max}}}$	Minimum inlet chamber air density
$\rho_{\mathrm{inMax}} = \frac{p_{\mathrm{inMax}}}{R_{\mathrm{A}} T_{2\mathrm{min}}}$	Maximum inlet chamber air density
$\rho_{\mathrm{mainMin}} = \frac{p_{\mathrm{mainMin}}}{R_{\mathrm{A}} T_{3\mathrm{max}}}$	Minimum main chamber air density
$\rho_{\mathrm{mainMax}} = \frac{p_{\mathrm{mainMax}}}{R_{\mathrm{A}} T_{3\mathrm{min}}}$	Maximum main chamber air density
$\rho_{\mathrm{outMin}} = \frac{p_{\mathrm{outMin}}}{R_{\mathrm{A}} T_{4\mathrm{max}}}$	Minimum outlet chamber air density
$\rho_{\mathrm{outMax}} = \frac{p_{\mathrm{outMax}}}{R_{\mathrm{A}} T_{4\mathrm{min}}}$	Maximum outlet chamber air density
$\dot{V}_{\mathrm{in,estMin}} = f(\rho_{\mathrm{inMax}}, A_{\mathrm{FB,in}}, p_{5\mathrm{min}})$	Minimum estimated air volume flow in input chamber
$\dot{V}_{\mathrm{in,estMax}} = f(\rho_{\mathrm{inMin}}, A_{\mathrm{FB,in}}, p_{5\mathrm{max}})$	Maximum estimated air volume flow in input chamber
$\dot{V}_{\mathrm{main,estMin}} = f\left(\rho_{\mathrm{mainMax}}, A_{\mathrm{FB,main}}, \frac{p_{6\mathrm{min}} + p_{7\mathrm{min}}}{2}\right)$	Minimum estimated air volume flow in main chamber

$\dot{V}_{\text{main,estMax}} = f\left(\rho_{\text{mainMin}}, A_{\text{FB,main}}, \frac{p_{6\max} + p_{7\max}}{2}\right)$ Maximum estimated air volume flow in main chamber

$\dot{V}_{\text{out,estMin}} = f\left(\rho_{\text{outMax}}, A_{\text{FB,out}}, p_{8\min}\right)$ Minimum estimated air volume flow in outlet chamber

$\dot{V}_{\text{out,estMax}} = f\left(\rho_{\text{outMin}}, A_{\text{FB,out}}, p_{8\max}\right)$ Maximum estimated air volume flow in outlet chamber

It can be shown that the minimum values of the estimated mass flows $\dot{m}_{\text{A,est}}$ need to be calculated with the maximum air densities ρ, and vice versa. This is caused by the function that calculates the estimated air volume flows $\dot{V}_{\text{est}}$.

$\dot{m}_{\text{A,in,estMin}} = \dot{V}_{\text{in,estMin}} \rho_{\text{inMax}}$ Minimum estimated air mass flow in input chamber

$\dot{m}_{\text{A,in,estMax}} = \dot{V}_{\text{in,estMax}} \rho_{\text{inMin}}$ Maximum estimated air mass flow in input chamber

$\dot{m}_{\text{A,main,estMin}} = \dot{V}_{\text{main,estMin}} \rho_{\text{mainMax}}$ Minimum estimated air mass flow in main chamber

$\dot{m}_{\text{A,main,estMax}} = \dot{V}_{\text{main,estMax}} \rho_{\text{mainMin}}$ Maximum estimated air mass flow in main chamber

$\dot{m}_{\text{A,out,estMin}} = \dot{V}_{\text{out,estMin}} \rho_{\text{outMax}}$ Minimum estimated air mass flow in outlet chamber

$\dot{m}_{\text{A,out,estMax}} = \dot{V}_{\text{out,estMax}} \rho_{\text{outMin}}$ Maximum estimated air mass flow in outlet chamber

$\dot{m}_{\text{A,estMin}} = \dot{m}_{\text{A,in,estMin}} + \dot{m}_{\text{A,main,estMin}} + \dot{m}_{\text{A,out,estMin}}$ Minimum estimated total air mass flow

$\dot{m}_{\text{A,estMax}} = \dot{m}_{\text{A,in,estMax}} + \dot{m}_{\text{A,main,estMax}} + \dot{m}_{\text{A,out,estMax}}$ Maximum estimated total air mass flow

$\dot{m}_{\text{A,inMin}} = \dot{m}_{\text{A,in,estMin}} \frac{\dot{m}_{\text{Amin}}}{\dot{m}_{\text{A,estMin}}}$ Minimum corrected mass flow in inlet chamber

$\dot{m}_{\text{A,inMax}} = \dot{m}_{\text{A,in,estMax}} \frac{\dot{m}_{\text{Amax}}}{\dot{m}_{\text{A,estMax}}}$ Maximum corrected mass flow in inlet chamber

$\dot{m}_{\text{A,mainMin}} = \dot{m}_{\text{A,main,estMin}} \frac{\dot{m}_{\text{Amin}}}{\dot{m}_{\text{A,estMin}}}$ Minimum corrected mass flow in main chamber

$\dot{m}_{\text{A,mainMax}} = \dot{m}_{\text{A,main,estMax}} \frac{\dot{m}_{\text{Amax}}}{\dot{m}_{\text{A,estMax}}}$ Maximum corrected mass flow in main chamber

$$\dot{m}_{\mathrm{A,outMin}} = \dot{m}_{\mathrm{A,out,estMin}} \frac{\dot{m}_{\mathrm{Amin}}}{\dot{m}_{\mathrm{A,estMin}}}$$ Minimum corrected mass flow in outlet chamber

$$\dot{m}_{\mathrm{A,outMax}} = \dot{m}_{\mathrm{A,out,estMax}} \frac{\dot{m}_{\mathrm{Amax}}}{\dot{m}_{\mathrm{A,estMax}}}$$ Maximum corrected mass flow in outlet chamber

$$p_{\mathrm{AinMin}} = p_{\mathrm{mainMin}} - \frac{p_{\mathrm{6max}} + p_{\mathrm{7max}}}{2}$$ Minimum fluidization air inlet pressure

$$p_{\mathrm{AinMax}} = p_{\mathrm{mainMax}} - \frac{p_{\mathrm{6min}} + p_{\mathrm{7min}}}{2}$$ Maximum fluidization air inlet pressure

$$T_{\mathrm{AinMin}} = T_{\mathrm{3min}}$$ Minimum fluidization air inlet temperature

$$T_{\mathrm{AinMax}} = T_{\mathrm{3max}}$$ Maximum fluidization air inlet temperature

$$T_{\mathrm{Amin}} = \frac{T_{\mathrm{AinMin}} + T_{\mathrm{AoutMin}}}{2}$$ Minimum mean fluidization air temperature

$$T_{\mathrm{Amax}} = \frac{T_{\mathrm{AinMax}} + T_{\mathrm{AoutMax}}}{2}$$ Maximum mean fluidization air temperature

$$\rho_{\mathrm{Amin}} = f\left(p_{\mathrm{AinMin}}, T_{\mathrm{Amax}}\right)$$ Minimum fluidization air density

$$\rho_{\mathrm{Amax}} = f\left(p_{\mathrm{AinMax}}, T_{\mathrm{Amin}}\right)$$ Maximum fluidization air density

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.

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

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

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

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

$$\dot{V}_{\mathrm{mf,mainMin}}=w_{\mathrm{mfMin}}\,A_{\mathrm{FB,main}}$$ Minimal minimum fluidization volume flow in main chamber

$$\dot{V}_{\mathrm{mf,mainMax}}=w_{\mathrm{mfMax}}\,A_{\mathrm{FB,main}}$$ Maximal minimum fluidization volume flow in main chamber

$$\mathrm{FG}_{\mathrm{min}}=\frac{\dot{m}_{\mathrm{A,mainMin}}}{\rho_{\mathrm{Amax}}\dot{V}_{\mathrm{mf,mainMax}}}$$ Minimum fluidization grade in main chamber

$$\mathrm{FG}_{\mathrm{max}}=\frac{\dot{m}_{\mathrm{A,mainMax}}}{\rho_{\mathrm{Amin}}\dot{V}_{\mathrm{mf,mainMin}}}$$ Maximum fluidization grade in main chamber

6.3 Ranges in Heat Transfer Coefficients

$$T_{\text{bed1min}} = \frac{T_{\text{bed11min}} + T_{\text{bed12min}} + T_{\text{bed13min}} + T_{\text{bed14min}}}{2}$$

Minimum mean bed temperature at first probe. T_{bed13min} and T_{bed14min} only exist in the finned tube experiments

$$T_{\text{bed1max}} = \frac{T_{\text{bed11max}} + T_{\text{bed12max}} + T_{\text{bed13max}} + T_{\text{bed14max}}}{2}$$

Maximum mean bed temperature at first probe T_{bed13max} and T_{bed14max} only exist in the finned tube experiments

$$T_{\text{bed2min}} = \frac{T_{\text{bed21min}} + T_{\text{bed22min}} + T_{\text{bed23min}} + T_{\text{bed24min}}}{2}$$

Minimum mean bed temperature at second probe. T_{bed23min} and T_{bed24min} only exist in the finned tube experiments

$$T_{\text{bed2max}} = \frac{T_{\text{bed21max}} + T_{\text{bed22max}} + T_{\text{bed23max}} + T_{\text{bed24max}}}{2}$$

Maximum mean bed temperature at second probe. T_{bed23max} and T_{bed24max} only exist in the finned tube experiments

$$\alpha_{\text{gross1min}} = \frac{U_{\text{1min}} I_{\text{1min}} \cos(\varphi_{\text{1max}})}{A(T_{\text{surf1max}} - T_{\text{bed1min}})}$$

Minimum gross heat transfer coefficient, first probe

$$\alpha_{\text{gross1max}} = \frac{U_{\text{1max}} I_{\text{1max}} \cos(\varphi_{\text{1min}})}{A(T_{\text{surf1min}} - T_{\text{bed1max}})}$$

Maximum gross heat transfer coefficient, first probe

$$\alpha_{\text{gross2min}} = \frac{U_{\text{2min}} I_{\text{2min}} \cos(\varphi_{\text{2max}})}{A(T_{\text{surf2max}} - T_{\text{bed2min}})}$$

Minimum gross heat transfer coefficient, second probe

$$\alpha_{\text{gross2max}} = \frac{U_{\text{2max}} I_{\text{2max}} \cos(\varphi_{\text{2min}})}{A(T_{\text{surf2min}} - T_{\text{bed2max}})}$$

Maximum gross heat transfer coefficient, second probe

$$\alpha_{\text{gross,meanMin}} = \frac{\alpha_{\text{gross1min}} + \alpha_{\text{gross2min}}}{2}$$

Minimum gross heat transfer coefficient, mean

$$\alpha_{\text{gross,meanMax}} = \frac{\alpha_{\text{gross1max}} + \alpha_{\text{gross2max}}}{2}$$

Maximum gross heat transfer coefficient, mean

$$\dot{Q}_{\text{lossMin}} = \dot{m}_{\text{A,mainMin}} \left(h(T_{\text{AoutMin}}) - h(T_{\text{AinMax}}) \right)$$

Minimum heat losses due to fluidization

$$\dot{Q}_{\text{lossMax}} = \dot{m}_{\text{A,mainMax}} \left(h(T_{\text{AoutMax}}) - h(T_{\text{AinMin}}) \right)$$

Maximum heat losses due to fluidization

$$\alpha_{\text{net1min}} = \frac{U_{\text{1min}} I_{\text{1min}} \cos(\varphi_{\text{1max}}) - \dot{Q}_{\text{lossMax}}/2}{A(T_{\text{surf1max}} - T_{\text{bed1min}})}$$

Minimum net heat transfer coefficient, first probe

$$\alpha_{\mathrm{net1max}} = \frac{U_{1\mathrm{max}} I_{1\mathrm{max}} \cos(\varphi_{1\mathrm{min}}) - \dot{Q}_{\mathrm{lossMin}}/2}{A(T_{\mathrm{surf1min}} - T_{\mathrm{bed1max}})}$$

Maximum net heat transfer coefficient, first probe

$$\alpha_{\mathrm{net2min}} = \frac{U_{2\mathrm{min}} I_{2\mathrm{min}} \cos(\varphi_{2\mathrm{max}}) - \dot{Q}_{\mathrm{lossMax}}/2}{A(T_{\mathrm{surf2max}} - T_{\mathrm{bed2min}})}$$

Minimum net heat transfer coefficient, second probe

$$\alpha_{\mathrm{net2max}} = \frac{U_{2\mathrm{max}} I_{2\mathrm{max}} \cos(\varphi_{2\mathrm{min}}) - \dot{Q}_{\mathrm{lossMin}}/2}{A(T_{\mathrm{surf2min}} - T_{\mathrm{bed2max}})}$$

Maximum net heat transfer coefficient, second probe

$$\alpha_{\mathrm{net,meanMin}} = \frac{\alpha_{\mathrm{net1min}} + \alpha_{\mathrm{net2min}}}{2}$$

Minimum net heat transfer coefficient, mean

$$\alpha_{\mathrm{net,meanMax}} = \frac{\alpha_{\mathrm{net1max}} + \alpha_{\mathrm{net2max}}}{2}$$

Maximum net heat transfer coefficient, mean

7 Appendix

BCS215

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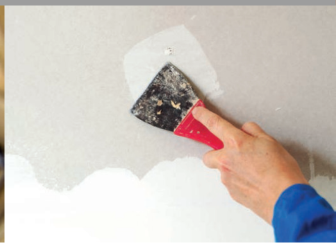

Chemische Analyse | Chemical analysis

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	0,146 mm
AFS Kennzahl | AFS number	91
Theoretische spezifische Oberfläche | Theoretic specific surface area	165 cm^2/g
Gleichmäßigkeitsgrad | Uniformity ratio	75 %
Glühverlust | Loss on ignition	< 0,2 %
Sinterbeginn | Sintering point	> 1550 °C
Schüttdichte feuergetrocknet | Bulk density fire dried	1,34 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	0,0		
0,355–0,500	0,0		
0,250–0,355	0,5	100,0	0–1
0,180–0,250	18,0	99,5	12–24
0,125–0,180	50,0	81,5	45–55
0,090–0,125	27,0	31,5	22–32
0,063–0,090	4,0	4,5	3–6
0,000–0,063	0,5	0,5	0–1

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.