Methodology

of

LINI 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_LINI" in the software repository and are based on data in the data repository (all .csv-files starting with LINI). 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

$l_{in}=l_{out}=0.15\ \text{m}$	Length of inlet / outlet chamber
$l_1=l_2=0.293\ \text{m}$	Length of first / second chamber
$l_{heated}=0.25\ \text{m}$	Heated tube length
$d=25\text{e-}3\ \text{m}$	Tube diameter
$A=d\,\pi\,l_{heated}$	Heated tube area
$A_{FB}=0.9\cdot 0.194\ \text{m}^2$	Fluidized bed grid area
$x_{heated}=\dfrac{l_1}{l_{in}+l_1+l_2+l_{out}}$	Fraction of fluidized bed containing the heated tube
$\Delta H_{eps}=50\,\text{mm}$	Heigh difference of pressure taps for porosity measurement
$d_p=146\text{e-}6\ \text{m}$	Mean particle diameter. The data sheet is in the appendix.
$\rho_p=2650\ \text{kg/m}^3$	Particle density (SiO_2)
$\rho_{A,norm}=1.293\ \text{kg/m}^3$	Air density at standard conditions
$g=9.81\,\text{m/s}^2$	Gravitational acceleration
$p_{amb}=1013.25\,\text{mbar}$	Ambient pressure

A sketch of the setup including some sensor positions is shown in Figure 1. The names are equal to the column names in the measurement csv files.

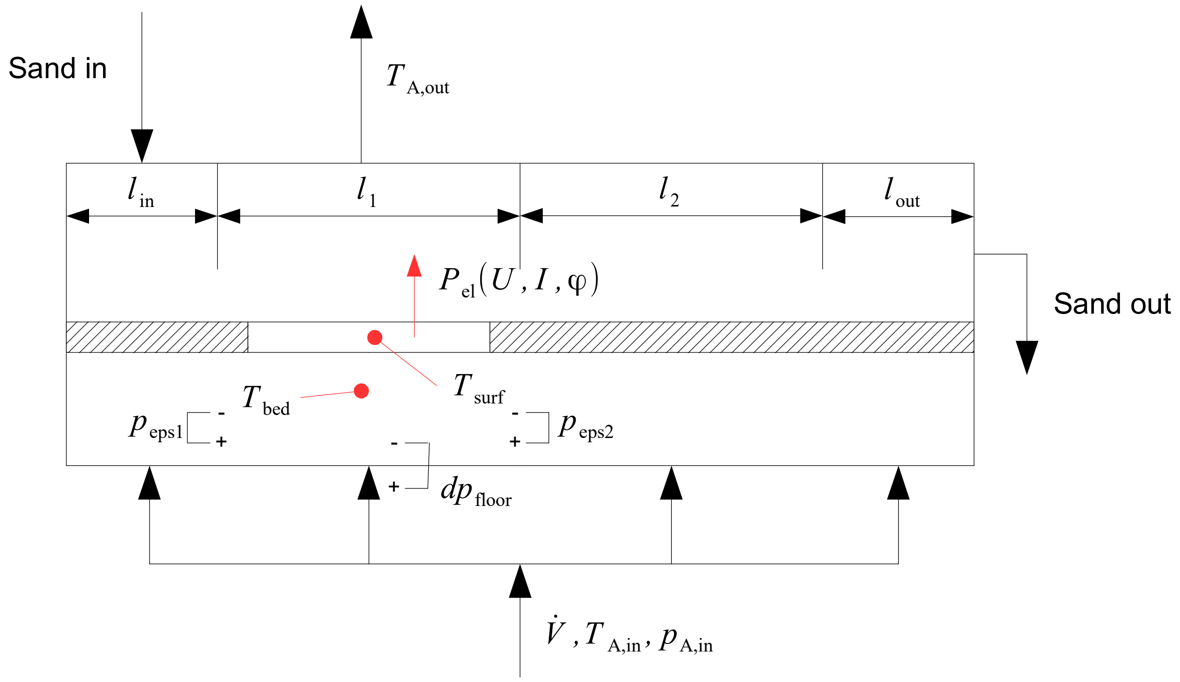

Figure 1: Measurement setup and sensor positions

The volume flow of the fluidization air was measured with a rotameter, see the equipment list in the data repository ("VdotRota" in the measurement csv files). The volume flow was corrected to the one at the actual operating pressure ("pRota") using a conversion tool provided by the supplier, which can be found in the data repository together with the necessary configuration files. The resulting volume flows for the mean values at each measurement period can be found in the csv files as "Vdot".

The bed temperature pictured in Figure 1 is the mean value of the two temperature measurements above and below the heated tube, see the design drawings.

For the calculation of the bed porosity, values beyond the measurement range of the pressure sensors (p_{eps1} and p_{eps2} in Figure 1) were ignored, which occurred intermittently due to high fluctuations.

Calculations

$$\varepsilon_1 = 1 - \frac{p_{\mathrm{eps1}}}{\rho_{\mathrm{p}}\, g\, \Delta H_{\mathrm{eps}}}$$ Bed porosity at position 1, see Figure 1

$$\varepsilon_2 = 1 - \frac{p_{\mathrm{eps2}}}{\rho_{\mathrm{p}}\, g\, \Delta H_{\mathrm{eps}}}$$ Bed porosity at position 2, see Figure 1

$$\varepsilon = \frac{\varepsilon_1 + \varepsilon_2}{2}$$ Mean bed porosity at the heated probe

$$p_{\mathrm{A}} = p_{\mathrm{amb}} + p_{\mathrm{A,in}} - dp_{\mathrm{floor}} + \rho\, g (1 - \varepsilon) \cdot 35\ \mathrm{mm}$$ Fluidization air pressure at the bed's bottom, derived from the inlet pressure, the pressure

loss across the sintered floor, and the static bed pressure 35 mm below the pressure tap of the negative side of dp_{floor} , see the design drawings in the repository

$$T_{\mathrm{A}}=\frac{T_{\mathrm{A,in}}+T_{\mathrm{A,out}}}{2}$$

Mean fluidization air temperature

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

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

$$\dot{V}=\dot{V}_{\mathrm{Norm}}\frac{\rho_{\mathrm{A,norm}}}{\rho_{\mathrm{A}}}$$

Mean volume flow, as explained above, at actual conditions

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

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

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

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

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

Minimum fluidization volume flow

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

Fluidization grade

$$\alpha_{\mathrm{gross}}=\frac{U\,I\cos(\varphi)}{A\left(T_{\mathrm{surf}}-T_{\mathrm{bed}}\right)}$$

Gross heat transfer coefficient

$$\dot{m}_{\mathrm{A,loss}}=\dot{V}\,\rho_{\mathrm{A}}\,x_{\mathrm{heated}}$$

Fluidization air mass flow causing heat losses in the heated chamber

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

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

$$\alpha_{\mathrm{net}}=\frac{U\,I\cos(\varphi)-\dot{Q}_{\mathrm{loss}}}{A\left(T_{\mathrm{surf}}-T_{\mathrm{bed}}\right)}$$

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
$T_{\mathrm{A,in}}$, $T_{\mathrm{A,out}}$, T_{bed} , T_{surf}	Thermometer	$\pm\left(0.15+0.002\frac{\lvert T\rvert}{°\mathrm{C}}\right)°\mathrm{C}$	Actual	See Description
	Transmitter	Offset: $\pm 0{,}0015\,\%\,\Omega$	Range	
		Gain: $\pm 0{,}0059\,\%\,\Omega$	Actual	
p_{eps1} , p_{eps2}	Sensor	$\pm 1\,\%$	Range	$X20AI4632\left(\pm 1\,\%\, p_{\mathrm{Range}}\right)$
	Transmitter	X20AI4632		
dp_{floor}	Sensor	$\pm 0.8\%$	Range	$X20AI4632\left(\pm 0.8\,\%\, p_{\mathrm{Range}}\right)$
	Transmitter	X20AI4632		
$p_{\mathrm{A,in}}$	Sensor	$\pm 0.5\%$	Range	$X20AI4632\left(\pm 0.5\,\%\, p_{\mathrm{Range}}\right)$
	Transmitter	X20AI4632		
$\dot{V}_{\mathrm{Norm}}$	Rotameter		Actual	$\dot{V} < 22\ \mathrm{Nm^3/h}:\ \pm 1\,\%\,\frac{22\ \mathrm{Nm^3/h}}{\dot{V}}$ $\dot{V} \geq 22\ \mathrm{Nm^3/h}:\ \pm 1\,\%$
U	Transmitter		Actual	$\pm 0.65\%$
I	Transformer	$\pm 1\,\%$	Actual	$\pm 1.707\,\%$
	Measurement	$\pm 0.7\%$	Actual	
φ	Transformer	$\pm 60'$	Actual	$\pm\left(0.5\,\%+60'\right)$
	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 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)
$p_{\mathrm{eps1}}, p_{\mathrm{eps2}}$	0	1 000
dp_{floor}	0	2 500
$p_{\mathrm{A,in}}$	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 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 :

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

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

Pressure ranges

$$bias_{\mathrm{p}} = \begin{cases} p_{\mathrm{eps1}}, p_{\mathrm{eps2}}:\ 1\,\%(MRE - MRB) \\ dp_{\mathrm{floor}}:\ 0.8\,\%(MRE - MRB) \\ p_{\mathrm{A,in}}:\ 0.5\,\%(MRE - MRB) \end{cases}$$

Bias of pressure measurements. MRB and MRE according to table 2.

Maximum and minimum values of pressure:

$$p_{\mathrm{eps1min}} = min_{\mathrm{CM}}(p_{\mathrm{eps1}} - bias_{\mathrm{p}}(p_{\mathrm{eps1}}), MRB(p_{\mathrm{eps1}}), MRE(p_{\mathrm{eps1}}))$$

$$p_{\mathrm{eps1max}} = max_{\mathrm{CM}}(p_{\mathrm{eps1}} + bias_{\mathrm{p}}(p_{\mathrm{eps1}}), MRB(p_{\mathrm{eps1}}), MRE(p_{\mathrm{eps1}}))$$

$\vdots$

Repeat for all pressure measurements

Temperature ranges

$$\Delta T = f(T) = 0.15 + 0.002 \cdot |T|$$

Observational error of all temperature values. T in °C

$T_{\text{surfSensorMin}} = T_{\text{surf}} - \Delta T(T_{\text{surf}})$	Minimum sensor value of T_{surf}
$T_{\text{surfSensorMin}} = T_{\text{surf}} + \Delta T(T_{\text{surf}})$	Maximum sensor value of T_{surf}
$R = f(T) = 100\,\Omega(1 + 3.9083\text{e-}3\,T - 5.775\text{e-}7\,T^2)$	Resistance of PT100 sensor at temperature T. Constants according to EN 60751
$gain_{\text{T}} = 0.0059\,\%$	Gain of temperature transmitter, see table 1
$R_{\text{surfMin}} = R(T_{\text{surfSensorMin}})(1 - gain_{\text{T}})$	Minimum resistance of temperature sensor
$R_{\text{surfMax}} = R(T_{\text{surfSensorMax}})(1 + gain_{\text{T}})$	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:

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

$T_{\text{surfMin}} = R^{-1}(R_{\text{surfMin}}) - offset_{\text{T}}$	Minimum value of T_{surf}
$T_{\text{surfMax}} = R^{-1}(R_{\text{surfMax}}) + offset_{\text{T}}$	Maximum value of T_{surf}
$\vdots$	Repeat for all temperature measurements

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

$$\Delta \dot{V} = f(\dot{V}, \dot{V}_{\text{Norm}}) = \left\{ \begin{array}{ll} \dot{V}_{\text{Norm}} < 22\ \text{Nm}^3/\text{h}: & \dfrac{\dot{V}_{\text{Air}}}{100} \dfrac{22\ \text{Nm}^3/\text{h}}{\dot{V}} \\ \dot{V}_{\text{Norm}} \geq 22\ \text{Nm}^3/\text{h}: & \dfrac{\dot{V}_{\text{Air}}}{100} \end{array} \right\}$$

$\dot{V}_{\min} = \dot{V} - \Delta \dot{V}(\dot{V}, \dot{V}_{\text{Norm}})$	Minimum value of $\dot{V}$
$\dot{V}_{\max} = \dot{V} + \Delta \dot{V}(\dot{V}, \dot{V}_{\text{Norm}})$	Maximum value of $\dot{V}$

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

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

3.2 Ranges in Degree of Fluidization

$$\varepsilon_{1min} = 1 - \frac{p_{eps1max}}{\rho_p g \Delta H_{eps}}$$ Minimum bed porosity at position 1

$$\varepsilon_{1max} = 1 - \frac{p_{eps1min}}{\rho_p g \Delta H_{eps}}$$ Maximum bed porosity at position 1

$$\varepsilon_{2min} = 1 - \frac{p_{eps2max}}{\rho_p g \Delta H_{eps}}$$ Minimum bed porosity at position 2

$$\varepsilon_{2max} = 1 - \frac{p_{eps2min}}{\rho_p g \Delta H_{eps}}$$ Maximum bed porosity at position 2

$$\varepsilon_{min} = \frac{\varepsilon_{1min} + \varepsilon_{2min}}{2}$$ Minimum mean bed porosity

$$\varepsilon_{max} = \frac{\varepsilon_{1max} + \varepsilon_{2max}}{2}$$ Maximum mean bed porosity

Minimum und maximum fluidization air pressures:

$$p_{Amin} = p_{amb} + p_{A,in,min} - dp_{floorMax} + \rho g (1 - \varepsilon_{max}) \cdot 35\,\mathrm{mm}$$

$$p_{Amax} = p_{amb} + p_{A,in,max} - dp_{floorMin} + \rho g (1 - \varepsilon_{min}) \cdot 35\,\mathrm{mm}$$

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

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

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

$$\rho_{Amax} = f(p_{Amax}, T_{Amin})$$ 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.

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

$\eta_{\mathrm{Amax}} = f(T_{\mathrm{Amin}})$ 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

$$\dot{V}_{\mathrm{mfMin}} = w_{\mathrm{mfMin}} A_{\mathrm{FB}}$$ Minimal minimum fluidization volume flow

$$\dot{V}_{\mathrm{mfMax}} = w_{\mathrm{mfMax}} A_{\mathrm{FB}}$$ Maximal minimum fluidization volume flow

$$\mathrm{FG}_{\mathrm{min}} = \frac{\dot{V}_{\mathrm{min}}}{\dot{V}_{\mathrm{mfMax}}}$$ Minimum fluidization grade

$$\mathrm{FG}_{\mathrm{max}} = \frac{\dot{V}_{\mathrm{max}}}{\dot{V}_{\mathrm{mfMin}}}$$ Maximum fluidization grade

3.3 Ranges in Heat Transfer Coefficients

$$\alpha_{\mathrm{grossMin}}=\frac{U_{\mathrm{min}} I_{\mathrm{min}} \cos(\varphi_{\mathrm{max}})}{A(T_{\mathrm{surfMax}}-T_{\mathrm{bedMin}})}$$ Minimum gross heat transfer coefficient

$$\alpha_{\mathrm{grossMax}}=\frac{U_{\mathrm{max}} I_{\mathrm{max}} \cos(\varphi_{\mathrm{min}})}{A(T_{\mathrm{surfMin}}-T_{\mathrm{bedMax}})}$$ Maximum gross heat transfer coefficient

$$\dot{m}_{\mathrm{Amin}}=\dot{V}_{\mathrm{min}}\rho_{\mathrm{A,norm}}$$ Minimum fluidization air mass flow

$$\dot{m}_{\mathrm{Amax}}=\dot{V}_{\mathrm{max}}\rho_{\mathrm{A,norm}}$$ Maximum fluidization air mass flow

$$\dot{Q}_{\mathrm{lossMin}}=\dot{m}_{\mathrm{Amin}}\left(h(T_{\mathrm{AoutMin}})-h(T_{\mathrm{AinMax}})\right)$$ Minimum heat losses due to fluidization

$$\dot{Q}_{\mathrm{lossMax}}=\dot{m}_{\mathrm{Amax}}\left(h(T_{\mathrm{AoutMax}})-h(T_{\mathrm{AinMin}})\right)$$ Maximum heat losses due to fluidization

$$\alpha_{\mathrm{netMin}}=\frac{U_{\mathrm{min}} I_{\mathrm{min}} \cos(\varphi_{1\mathrm{max}})-\dot{Q}_{\mathrm{lossMax}}}{A(T_{\mathrm{surfMax}}-T_{\mathrm{bedMin}})}$$ Minimum net heat transfer coefficient

$$\alpha_{\mathrm{netMax}}=\frac{U_{\mathrm{max}} I_{\mathrm{max}} \cos(\varphi_{1\mathrm{min}})-\dot{Q}_{\mathrm{lossMin}}}{A(T_{\mathrm{surfMin}}-T_{\mathrm{bedMax}})}$$ Maximum net heat transfer coefficient

4 Appendix

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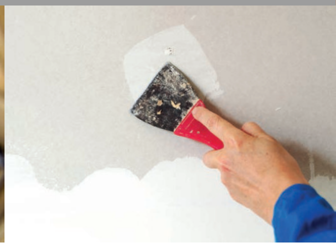

Chemische Analyse | Chemical analysis

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.

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