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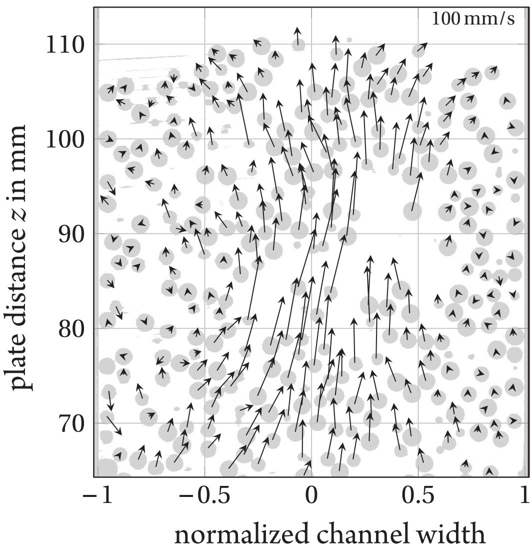
Katrin Kelm

Particle Flow within the Pulsed Liquid-Solid Fluidized Bed



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BAND 45

Hrsg.: Prof. Dr.-Ing. E. Schlücker

Particle Flow within the Pulsed Liquid-Solid Fluidized Bed

Die Bewegung von Partikeln in der gepulsten
Flüssigkeits-Feststoff-Wirbelschicht

Der Technischen Fakultät
der Friedrich-Alexander-Universität
Erlangen-Nürnberg

zur

Erlangung des Doktorgrades Dr.-Ing.

vorgelegt von
Katrin Kelm
aus Solingen

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"In all affairs it’s a healthy thing now and then to hang a question mark on the things you have long taken for granted."

Bertrand Russell

Preamble

The presented work and experimental research has been realized at the *Institute of Process Machinery and Systems Engineering* (iPAT), which is part of the *Friedrich-Alexander-University of Erlangen-Nuremberg* (FAU). So most of all, I would like to express my gratitude to Prof. Dr.-Ing. Eberhard Schlücker, who gave me the great opportunity to work on this challenging, multidisciplinary topic.

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No scientific work can ever be done by a single person without the backup of a bunch of people involved. A colorful mixture of doctoral candidates, students, various co-workers, technicians, the workshop staff and professors ensured, that for every question there was always at least one contact helping to pave the way forward. This includes technical support and practical skills of the technical staff as well as all the discussions with doctoral candidates from different institutes and the SAOT. Big challenges of the particle setup I passed with the help of Prof. Dr.-Ing. habil. Karl-Ernst Wirth and Prof. Dr.-Ing. Andreas Bück. Quite unexpected support, I found straying across several scientific conferences: Joshua, I would like to thank you for accelerating my research by sharing background knowledge about LIF experimental setups and materials. And Tim, my dear dutch PhD buddy: thank you a lot for the deepest of all scientific thought exchanges, for many funny hours and of course for getting me out of that Nuremberg parking lot!

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Last, I would like to thank my husband Sebastian, my mother Jutta, my father Dirk, my brother Michael, my whole family and my friends for years of bearing my restless mind and scientific attitude, having my head in the clouds all day long. All of you never got tired to remind me, that there is nothing more important than being understood, loved, healthy and enjoying a good time with each other. To my horsey companion Sun: so right you are →all you need is a mind that is free, some awareness & empathy... and of course good oats!

Abstract

Hydraulic transport with reciprocating positive displacement pumps offers great opportunities to transport tons of particulate solids over large distances. Using the pressure rigid operating principle provides very high pressure, yet predicting the impact of the unsteady drive kinematics on flow fields and particle motion is challenging. Few is known about the physical interaction at phase boundaries for liquid-solid flows against gravity on microscopic levels. Especially lack of knowledge under accelerated flow condition make it difficult to estimate the transport efficiency and reliability of new pump plants. In order to mimic the liquid-solid particulate system under pulsed flow condition, an experimental fine-tunable flow setup with a well-defined fluidized bed has been established. An acquiring method based on simultaneously flow measurement and imaging techniques for gathering extensive, time-resolved data of particle motion and flow has been developed and applied for different input parameters. First evaluation approaches have been suggested and applied to each parameter set in order to elaborate potential usage and limitations. Results of the parameter study gave first impressions about how pulse duration, flow amplitude and solid volume fraction affect particle motion. While deep knowledge of particle motion and movement patterns can be directly obtained from the image data, valuable correlations could be found between detailed particle motion and macroscopic bed parameters such as bed height and pressure loss.

Kurzfassung

Der hydraulische Transport mit oszillierenden Verdrängerpumpen bietet effizente Möglichkeiten, große Mengen an pulverförmigen Medien über weite Entfernungen zu befördern. Die dazu erforderlichen hohen Drücke können durch das drucksteife Arbeitsprinzip der Kolbenpumpe hervorragend bereitgestellt werden. Dennoch besteht infolge der Antriebskinematik der Nachteil, dass sich die Bewegung des Partikelkollektivs innerhalb des resultierenden gepulsten Strömungsfeldes schlecht vorhersagen lässt. Über die physikalischen Wechselwirkungen an den Phasengrenzflächen für Fluid-Feststoff-Strömungen ist auf mikroskopischer Ebene wenig bekannt. Insbesondere fehlende Kenntnisse über die Partikelbewegung unter beschleunigten Strömungsbedingungen entgegen der Schwerkraft machen es schwierig, die Transporteffizienz neuer Pumpenanlagen vorherzusagen und die zuverlässige Funktion der Anlagen sicherzuestellen.

Um Einblick in die Bewegungsmuster von Partikeln im gepulsten Strömungsfeld zu erhalten, wurde im Rahmen der vorliegenden Arbeit ein experimenteller Aufbau realisiert, der das dreidimensionale Verhalten einer Flüssigkeits-Feststoff-Wirbelschicht abbildet. Basierend auf den bewusst idealisiert gewählten Wirbelschichtparametern wurde eine Erfassungsmethode entwickelt, die zeitaufgelöst die vorherrschenden Strömungsparameter des Fluids dem Bewegungsmuster des Partikelkollektivs gegenüberstellt. Verschiedene Auswertemethoden wurden auf eine

begrenzte Anzahl an Parametervariationen angewandt, um die Vor- und Nachteile der Methoden sowie mögliche Grenzen zu ermitteln.

Die Ergebnisse der Parameterstudie gaben erste Eindrücke darüber, wie Pulsdauer, Strömungsamplitude und Feststoffanteil die Partikelbewegung beeinflussen. Während die Daten aus dem bildgebenden Verfahren tiefreichende Erkenntnisse darüber geben, wie das Partikelströmungsfeld auf verschiedene Parameter reagiert, konnten erste Korrelationen zwischen dem Antwortverhalten des Partikelströmungsfeldes und den makroskopischen Wirbelschichtparametern Betthöhe und Druckverlust gewonnen werden.

Contents

List of Symbols and Abbreviations

Symbol	**Definition**	**Unit**
A	Area	m^2
A_0	Superficial flow area / channel cross section	m^2
A_{eff}	Effective flow area	m^2
$a_{f,sf}$	Superficial fluid acceleration	m/s^2
$a_{p,w}$	Particle acceleration in z-direction	m/s^2
$\vec{a}_p$	Resulting particle acceleration	m/s^2
Ar	Archimedes number	-
B	Permeability constant	-
c_d	Drag coefficient	-
$c_{d,sph}$	Drag coefficient of a sphere	-
$d_1 - d_5$	Distances of the laser beam	m
d_{tr}	Trajectory waist	m
d_p	Particle diameter	m
$\bar{d}_p$	Sauter mean particle diameter	m
$E_{kin,f}$	Kinetic fluid energy	J
$E_{kin,p}$	Kinetic particle energy	J
$F_{p,B}$	Buoyancy force acting on a particle	N
$F_{p,D}$	Drag force acting on a particle	N
$F_{p,W}$	Weight force acting on a particle	N
g	Gravity	m/s^2
h	Height of the expanded fluidized bed	m
h_0	Height of the fixed bed	m
h_m	Manually determined bed's height	m
i	Image number; sum index	-

Symbol	Definition	Unit
k	Constant of the limited growth function	-
L_x, L_y, L_z	Channel dimensions	m
$M = (x/\Theta)$	Ray matrix with distance x and angle Θ	-
$M_{T,CL}$	Transfer matrix for the cylindrical lens	-
$M_{T,PL}$	Transfer matrix for the Powell lens	-
n	Refractive index; sum upper limit	-
n_p	Pulse number	-
p	Pressure	bar
p_1	Absolute system pressure at channel entry	bar
p_d	Discharge pressure	bar
p_s	Suction pressure	bar
$p_{g,1}$	Gauge pressure at damper 1	bar
$p_{g,2}$	Gauge pressure at damper 2	bar
Δp	Differential pressure	bar
Δp_{fb}	Pressure drop along the fluidized bed	bar
$\Delta p_{fb,mf}$	Pressure drop Δp_{fb} at minimum fluidization	bar
$\Delta p_{fb,ref}$	Differential reference pressure (empty channel)	bar
$\Delta p_{fb,pl}$	Plateau pressure drop along the fluidized bed	bar
Δp_{tot}	Pressure drop along the fluidized bed and plate	bar
$\Delta P/\Delta L$	Pressure drop per length unit (Ergun)	bar/m
S_V	Specific surface area	m^{-1}
S	Variable of the limited growth function	-
S_0	Value of the limited growth function at t=0	-
S_L	Limit of the limited growth function	-
t	Time	s
Δt_p	Time interval	s
T	Temperature	°C
T_0	Temperature in the reservoir	°C
T_1	Temperature at channel entry	°C
T_2	Temperature at channel exit	°C
V_v	Void volume	m^3
$V_{v,0}$	Void volume of the fixed bed	m^3
V_0	Bulk volume	m^3
$V_{p,tot}$	Total volume occupied by particles	m^3

Symbol	Definition	Unit
$\vec{v}_{\mathrm{p,res}}$	Resulting particle velocity	m/s
$w_{\mathrm{f,mf}}$	Minimum fluidization velocity	m/s
$w_{\mathrm{f,sf}}$	Superficial fluid velocity	m/s
$w_{\mathrm{f,t}}$	Terminal fluid velocity	m/s
$w_{\mathrm{f,int}}$	Interstitial fluid velocity	m/s
$w_{\mathrm{f,int,eff}}$	Effective interstitial fluid velocity	m/s
w_{p}	Particle velocity	m/s
$w_{\mathrm{p,sw}}$	Particle swarm settling velocity	m/s
$w_{\mathrm{p,t}}$	Terminal velocity of a particle	m/s
$w_{\mathrm{p,t,sph}}$	Terminal velocity of a sphere	m/s
$w_{\mathrm{p,eff}}$	Effective velocity of a particle	m/s
w_{p}^{+}	Particle transport velocity	m/s
$u_{\mathrm{p}}, v_{\mathrm{p}}, w_{\mathrm{p}}^{-}$	Particle loss velocities in direction x, y, $-z$	m/s
$u_{\mathrm{p}}^{*}, w_{\mathrm{p}}^{*}, \vec{v}_{\mathrm{p,res}}^{*}$	Spatially resolved particle velocities	m/s
x, y, z	Channel coordinates	-
q	Flow rate	l/h
$\dot{\gamma}$	Shear rate	s^{-1}
ϵ	Voidage of the fluidized bed	-
ϵ_0	Voidage of the fixed bed	-
ϵ_{i}	Initial voidage of the fluidized bed	-
$(1-\epsilon)$	Solid volume fraction	-
$(1-\epsilon)_0$	Solid volume fraction of the fixed bed	-
$(1-\epsilon)_{\mathrm{i}}$	Initial solid volume fraction of the fluidized bed	-
η_{f}	Fluid efficiency	-
η_{p}	Particle entrainment efficiency	-
η_{tot}	Total entrainment efficiency	-
λ	Wavelength	m
λ_{ex}	Excitation wavelength (max. laser intensity)	m
λ_{on}	Cut-on wavelength of longpass filter	m
μ	Dynamic viscosity	Pa s
ν	Kinematic viscosity	m^2/s
ρ_{f}	Density of the fluid phase	kg/m^3
ρ_{s}	Density of the solid phase	kg/m^3
Ψ	Sphericity factor	-

Abbreviation	Definition
C2	Camera height 2 with specific initial SVF
C3	Camera height 3 with specific initial SVF
CFD	Computational fluid dynamics
CH	Channel
CL	Cylindrical lens
colSVF	Column-wise calculated SVF
DAQ	Data acquisition device
DEM	Discrete element method
EHD	Elliptical holographic diffusor
fB	Steady-state fluidized bed
FFT	Fast Fourier Transform
FOP	Fibre optical probe
FOV	Field of view
ID1	Voronoi target particle ID
ID2	Voronoi candidate particle ID
LDV	Laser doppler velocimetry
LES	Large eddy simulation
LIF	Laser induced fluorescence
LRF	Linear Regression Function
MDSR	Multidirectional stripe remover
PFV	Photron Fastcam Viewer
PIV	Particle image velocimetry
PL	Powell lens
PLC	Programmable logic controller
PLIF	Planar laser-induced fluorescence
PTV	Particle tracking velocimetry
pfB	Pulsed fluidized bed (measurements with particles)
RI	Refractive index
RIM	Refractive index matching
RIMS	Refractive index matched scanning
rowSVF	Row-wise calculated SVF
SA	Slit aperture
sfC	Superficial characteristic (empty pipe measurements)

Abbreviation	Definition
SVF	Solid volume fraction
SWF	Solid weight fraction
Q2D	Quasi-2-dimensional setup