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Falah Alobaid

Numerical Simulation for Next Generation Thermal Power Plants

Springer

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Static is simple, but the universe is dynamic

Falah Alobaid

Foreword

The conventional design of thermal power plants mainly focuses on high process efficiency, while market requirements more and more target operation flexibility due to the increased penetration of renewable energy sources. Five major approaches to maintain the supply security of future electricity systems are distinguishable in general:

(1) Expansion of high-voltage transmission infrastructure: The adequate addition of high-voltage transmission infrastructure in combination with smart power electronics is essential to accommodate the growing renewable capacity and ensures security of supply. By increasing the number of interconnections between major load centres, the transmission capacity and robustness of the electricity grid can be greatly improved. For sufficient flexibility of the overall system, the grid expansion must be complemented by additional measures. Environmental and political challenges are common causes for the delayed expansion of grid infrastructure.

(2) Enrolment of demand response: Demand response is the ability of end users to reduce load according to price signals or dispatch rules. This measure can be applied to mitigate or counteract short-term grid imbalances.

(3) Modification to system operations: Improved forecasting decreases the uncertainty in net load, resulting in reduced utilisation of expensive peaking capacity and a cost-effective modification of system operations. Both (2) and (3) are support measures under development with the potential to effectively reduce costs associated with the transformation of the energy system.

(4) Large-scale energy storage (also called grid-energy storage): These systems can be charged or discharged flexibly to allow for high shares of renewable electricity feed-in. Grid-energy storage is, in theory, ideally suited to balance intermittent power supply and demand. Pumped hydroelectric storage is commonly used, but it is limited to suitable geographical conditions. Other technologies in various stages of development include battery energy storage, flywheel energy storage, compressed air energy storage, power-to-gas and thermal energy storage. Despite recent advances in battery storage driven by the

automotive industry, the specific costs of storage systems still limit their use to small-scale applications and there is currently no economically viable storage technology available for the required capacities (TWh rather than MWh).

(5) Flexibility improvement of existing infrastructure of electricity supply (dispatchable power generation): This approach represents the most economic option for increasing system flexibility. In many countries without abundant natural resources suitable for large hydro or geothermal energy, power generation is mainly based on thermal power plants and will continue to do so in the foreseeable future, considering plant lifetime of up to 40 years. The operating flexibility of thermal power plants is limited by technical constraints such as ramp rates and minimum load limit. Existing power plants can be retrofitted with optimised components and control circuits to mitigate these constraints and to meet enhanced flexibility requirements. Highly dispatchable generating units such as combined-cycle power plants and gas engines are also available to replace outdated plants.

This book is built around the approach of the dispatchable generating units and offers significant benefits to students, engineers, researchers and industrial experts. Mathematical models including one-dimensional dynamic process simulation and three-dimensional computational fluid dynamics (CFD) are developed and validated with the operation data from real plants. The book can be divided into three main parts:

- In the first part, the mathematical background for the one-dimensional dynamic process modelling of thermal power plants is shown. The thermal hydraulic models such as the mixture flow model and the two-fluid flow models are explained in detail. Furthermore, the process, automation and electrical components required for the dynamic simulation of energy systems are described.
- The second part presents the mathematical background for the three-dimensional CFD simulation of gas-solid flows such as quasi-single-phase, two-fluid and single-particle methods. The focus is on the discrete element method, including the forces and the moments of force acting on particles. Here, the determination of inter-phase values (volumetric void fraction, momentum and heat transfers) is carried out using a new procedure known as the offset method. Furthermore, the particle-grid method that allows the refinement of the grid resolution independent of the particle size is introduced.
- The last part shows relevant results on dynamic process simulations for different technologies of combined-cycle power plant, pulverised coal-fired power plant, concentrated solar power plant and municipal waste incinerator. Furthermore, the application of CFD models to different energy systems is shown as well, e.g. 1 MWth combustion chamber, 1 MWth fluidized bed, 60 MWth waste incinerator, large-scale lignite and hard coal-fired power plants. Measurements obtained from real energy systems are applied to validate the process and CFD simulation models.

My gratitude is pointed to the author, who achieved a great contribution to the field of theoretical modelling and practical application of energy systems. The extensive review for this book summarises state-of-the-art modelling techniques ranging from 1D steady-state and dynamic approaches to 3D-CFD reactor models with high reference to industry applications. The author can be sure that there will be many grateful readers benefiting from the detailed summary on mathematical formulations for the one-dimensional dynamic process simulations and the three-dimensional computational fluid dynamics models, not only because the modelling gained particular importance nowadays, but also of the comprehensively way of writing. Once again, I would like to thank the author for his considerable efforts in writing this book.

Darmstadt, Germany
March 2018

Bernd Epple
Technische Universität Darmstadt

Preface

This book provides researchers, developers and practitioners with a major contribution to mathematical models' developments (including one-dimensional dynamic process simulation and three-dimensional computational fluid dynamics (CFD)) and their applications to various energy systems (e.g. combined-cycle power, pulverised coal-fired power, concentrated solar power and fluidized bed systems).

Process, automation and electrical components as well as the mathematical background for process modelling, i.e. the mixture flow model and the two-fluid flow models (four-equation, five-equation, six-equation and seven-equation flow model), are explained in detail. CFD numerical methods for the modelling of gas–solid flows (quasi-single-phase, two-fluid and single-particle methods) are presented, too. Special attention is given to the discrete element method, including the forces and the moments of force acting on particles. Relevant studies that describe the application of dynamic process simulations and CFD models to different energy systems are shown. Measurements obtained from real thermal power plants are used to validate the process and CFD simulation models.

The book entitled "Numerical Simulation for Next Generation Thermal Power Plants" is based on my habilitation thesis and represents the results obtained during my time at the Department of Energy Systems and Technology at the Technische Universität Darmstadt.

I would like to express my gratitude to

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Darmstadt, Germany
March 2018

Falah Alobaid

Contents

Nomenclature

Latin Symbols

A	Surface, vessel cross-section area, pre-exponential factor [m^2], [m^2], [1/s]
a	Translational acceleration [m/s^2]
B	Magnetic flux density [N/A m]
b	Angular acceleration [rad/s^2]
C	Coefficient, correction factor [–], [–]
c	Concentration [kmol/m^3]
c_p	Specific heat capacity [J/kg K]
D	Surface diffusion coefficient, volume diffusion coefficient, diameter [m^2/s], [m^3/s], [m]
d	Displacement, diameter [m], [m]
E	Young's modulus, electric field intensity, energy, rate of entrainment [N/m^2], [N/A s], [J], [–]
e	Restitution coefficient [–]
F	Force [N]
f	Force density [N/m^3]
G	Shear modulus, particle acceleration [N/m^2], [m/s^2]
g	Standard gravity [m/s^2]
H	Pump head [m]
h	Enthalpy, height, rotation unit vector [kJ/kg], [m], [–]
$\mathbf{I}$	Unit matrix [–]
I	Moment of inertia, current [kg m^2], [A]
J	Impulse vector, superficial velocity [kg m/s], [m/s]
K	Stodola coefficient, heat transfer coefficient [–], [W/m^2 K]
k	Stiffness coefficient, reaction rate constant [N/m], [1/s]
k_R	Rotational stiffness coefficient [s]
l	Length [m]

M	Moment of force, molar mass [N m], [kg/kmol]
m	Mass [kg]
$\dot{m}$	Mass flow rate [kg/s]
N	Number of particle [–]
n	Number of north magnetic poles [A m]
P	Power [W]
p	Static pressure [N/m^2]
Q	Heat flow, capacity [*J*], [*A s*]
q	Charge, rate of heat flow [A s], [J/*s*]
$\mathbf{R}$	Rotation matrix [–]
R	Radius, rate of stratification, resistance [m], [–], [Ω]
r	Radius, position vector, reaction rate [m], [m], [kmol/m^3 s]
S	Source term, saturation level [different], [–]
s	Distance, unit vector [m], [–]
$\mathbf{T}$	Stress tensor for Newtonian fluids [N/m^2]
T	Torque, temperature, computing time [N m], [K], [s]
t	Time [s]
U	Electric potential, internal energy, voltage [kg m^2/A s^3], [J], [V]
u	Translational velocity [m/s]
V	Volume, velocity [m^3], [m/s]
$\dot{V}$	Volume flow rate [m^3/s]
W	Weight [kg]
w	Angular velocity [rad/s]
X	Mass fraction, molar fraction [kg/kg$_{\text{mix}}$], [mol/mol$_{\text{mix}}$]
x	Steam concentration [kmol/m^3]
x, y, z	Cartesian coordinates [m]

Greek Symbols

α	Heat transfer coefficient, collision angle [W/K m^2], [rad]
α_{UDS}	Blending factor [–]
β	Resistance coefficient, restitution coefficient, diffusion parameter [kg/s m^3], [–], [–]
γ	Surface tension, isentropic exponent [N/m], [–]
δ	Penetration depth, diameter [m], [m]
e	Restitution coefficient [–]
ε	Volumetric void fraction (porosity), emissivity [–], [–]
Γ	Mass transfer [kg/s m^3]
η	Damping coefficient, rolling damping constant, polytropic expansion efficiency, efficiency [N s/m], [kg m^2/s], [–], [–]
θ	Contact angle, inclination angle [rad], [rad]
λ	Thermal conductivity, bulk viscosity [W/K m], [kg/m s]

μ	Dynamic viscosity, friction coefficient, relative permeability [kg/m s], [–], [–]
μ_r	Rolling friction coefficient [m]
ξ	Fill angle [rad]
ω	Angular velocity [rad/s]
ρ	Density [kg/m^3]
σ	Surface tension [N/m]
τ	Viscous stress, stress tensor [N/m^2], [N/m^2]
ν	Poisson's number, stoichiometric coefficient, specific volume [–], [–], [m^3/kg]
ϕ	Physical value [different]
φ	Angular displacement, rotation angle, internal friction angle, surface charge [rad], [rad], [rad], [A s/m^2]
Θ	Granular temperature [m^2/s^2]
χ	Void fraction [–]
Ω	Computational domain [–]
$\partial\Omega$	Grid surface [m^2]
Π	Pressure ratio [–]

Constants

A	Hamaker constant [kg m^2/s^2]
a	Lattice constant [m]
c	Speed of sound, speed of light [m/s], [m/s]
h	Planck's constant [kg m^2/s]
k_B	Boltzmann's constant [kg m^2/s^2 K]
R	Universal gas constant [N m/kmol K]
ε_0	Absolute permittivity (electric constant) [A^2 s^4/kg m^3]
ε_{rel}	Relative permittivity (dielectric constant) [–]
λ	London constant [kg m^8/s^2]
σ	Stefan–Boltzmann constant [kg/s^3 K^4]
hw	Lifshitz-van der Waals constant [kg m^2/s^2]

Dimensionless Numbers

Kn	Knudsen number
Pe	Peclet number
Pr	Prandtl number
Re	Reynolds number
Sc	Schmidt number
Stk	Stokes number

Subscripts and Indices

acc	Accumulation
adh	Adhesion
ads	Adsorption
air	Air
ann	Annular
aper	Aperture
attemp	Attemperator
ave	Average
Bac	Backward
Bas	Basset
bc	Boundary condition
Beet	Beetstra
bin	Binary
bio	Biomass
blow	Blow-down
Boud	Boudouard
bub	Bubble
buo	Buoyancy
CV	Control volume
calc	Calcination
cap	Capillary
carb	Carbonation
cav	Cavity
cha	Char
char	Characteristic
clean	Cleanliness
col	Collision
cool	Cooling
com	Compressor
con	Contact
cont	Control
conv	Convection
cpl	Close packing limit
cri	Critical
D	Dimensional, derivative
DC	Device control
dam	Damping
den	Denominator
der	Derivation
dif	Diffusion
dis	Displaced
down	Downcomer

dra	Drag
dro	Droplet
dru	Drum
dust	Dust
dyn	Dynamic
Erg	Ergun
e	East
ela	Elastic
ele	Electric
elst	Electrostatic
end – los	End-loss
eq	Equilibrium
equ	Equivalent
ext	External
FF	Feedforward
Fos	Foscolo
f	Fluid or function
$f \rightarrow P$	Fluid to particle
fg	Flue gas
fil	Filter
fin	Final
flu	Fluid
for	Forward
fri	Frictional
fuel	Fuel
fw	Feedwater
Gar	Garside
Gid	Gidaspow
g, gas	Gas
gra	Gravitation, grain
Hertz	Hertz’s theory
Hooke	Hooke’s theory
h	Hydraulic, heat
het	Heterogeneous
hom	Homogeneous
hor	Horizontal
I	Integral
IAM	Incidence angle modifier
i	Component, notation, particle index
ilme	Ilmenite
in	Inner
inl	Inlet
int	Internal, interfacial, inter-stage, integration
isen	Isentropic
iwal	Particle i-wall

j	Component, notation, particle index
Koch/Hill	Koch and Hill
k	Component, notation
kin	Kinetic
l, liq	Liquid
lift	Lift
lin	Linear
loc	Located
load	Load
low	Lower
Mags	Magnus
m	Mixture
mag	Magnetic
mas	Mass
max	Maximum
mech	Mechanical
mem	Memory
min	Minimum
NC	Non-condensable
n	Normal, north
nec	Neck
nom	Nominal
num	Numerator
OC	Oxygen carrier
opt	Optical
out	Outer, outlet
ox	Oxidation
P	Particle, cell centre, proportional
$P \rightarrow f$	Particle to fluid
PP	Particle–particle
Pwal	Particle-wall
par	Parcel
pre	Pressure
pu	Pump
pyr	Pyrolysis
R	Rotation
r	Rolling
rad	Radiometric, radiation, radial
rc	Raw coal
ref	Reference, refractive
rel	Relative
relax	Relaxation
res	Resultant
riser	Riser
S	Shear flow

s	Solid, surface, south
Saf	Saffman
Sya	Syamlal and O'Brien
sat	Saturation
sca	Scattered
sep	Separation
sg	Search grid
sgc	Search-grid cell
$shad$	Shadowing
sin	Sintering
$slide$	Slide
sol	Solid bridge
$sorb$	Sorbent
ss	Solid–solid interaction
st	Steam
sta	Stack
$static$	Static
sto	Storage
$stop$	Stop
sub	Sub-cooling
sup	Superficial, superheating
sur	Surround
T	T-transition
t	Tangential
ter	Terminal
the	Theoretical
tot	Total
tra	Transition
$track$	Tracking
tur	Turbulent
$turb$	Turbine
u	Momentum
up	Upper
V	Volume
vac	Vacuum
val	Valve
van	Van der Waals
ver	Vertical
ves	Vessel
vir	Virtual
vm	Virtual mass
$Wen\&Yu$	Wen and Yu
w	West, wall
waf	Water- and ash-free
wal	Wall

wat	Water
–	Average
^	Non-dimensional
0	Initial, standard, reference
(0)	Before the collision, before the contact

Chemical Symbols

Ar	Argon
C	Carbon
CaO	Calcium oxide
$CaCO_3$	Calcium carbonate
CH_4	Methane
C_2H_4	Ethane
C_2H_6	Ethane
C_3H_8	Propane
CO	Carbon monoxide
CO_2	Carbon dioxide
COS	Carbonyl sulphide
Fe_2O_3	Ferric oxide
$FeTiO_3$	Ilmenite
H_2	Hydrogen
H_2O	Water
H_2S	Hydrogen sulphide
HCl	Hydrogen chloride
N_2	Nitrogen
NO	Nitric oxide
NO_2	Nitrogen dioxide
NO_x	Nitrogen oxides
O_2	Oxygen
TiO_2	Titanium dioxide
SO	Sulphur monoxide
SO_2	Sulphur dioxide
SO_x	Sulphur monoxide/dioxide/trioxide

Abbreviations

ABB	Asea Brown Boveri (multinational corporation)
AC	Alternating current
AF	Auxiliary fan
ANSYS	Commercial CFD software
APH	Air preheater
ASME	American Society of Mechanical Engineers

ASPEN	Commercial process simulation programme
APROS	Commercial process simulation programme
BARRACUDA	Commercial CFD software
BDS	Backward difference scheme
BFP	Boiler feedwater pump
BMCR	Boiler maximum continuous rating
BTL	Biomass to liquid
BUS	Burn-out supply
CAES	Compressed air storage system
CCL	Calcium carbonate-looping
CCPP	Combined-cycle power plants
CCS	Carbon capture and storage
CCV	Circulation control valve
CDS	Central differencing scheme
CFB	Circulating fluidized bed
CFD	Computational fluid dynamics
CIRC	Circulation
CLC	Chemical-looping combustion
CP	Circulation pump
CPFD	Computational particle fluid dynamics
CPH	Condensate preheating
CPU	Central processing unit
CSP	Concentrated solar power
CVFEM	Control volume based finite element method
D	Derivative controller
1D	One-dimensional
2D	Two-dimensional
3D	Three-dimensional
DB	Dead band value
DBS	In-house process simulation programme
DC	Direct current
DEM	Discrete element method, diffuse element method
DEMEST	In-house CFD/DEM code
DFGD	Dry flue gas desulfurization
DNI	Direct normal irradiance
DNS	Direct numerical simulation
DO	Discrete ordinates
DOOSAN	Multinational corporation
DTRM	Discrete transfer radiation model
DYMOLA	Commercial process simulation programme
EBSILON	Commercial process simulation programme
ECO	Economiser
EDC	Eddy dissipation concept
EDM	Eddy dissipation model
EFG	Element-free Galerkin method

EMMS	Energy minimisation multiscale
EST	Energy systems and technology department
ESP	Electrostatic precipitator
EVA	Evaporator
FD	Finite difference method
FDS	Forward difference scheme
FE	Finite element method, feedforward controller
FG	Flue gas
FGC	Flue gas condenser
FTT	Fast Fourier transform
FUNC	Function
FV	Finite volume method
GE	General Electric (multinational corporation)
GGH	Gas–gas heat exchanger
GIMP	Raster graphics editor (programme)
GT	Gas turbine
HCE	Heat collection element
HFO	Heavy fuel oil
HP	High pressure
HPBPCV	High-pressure bypass control valve
HPMSCV	High-pressure main steam control valve
HRA	Heat recovery area
HRSG	Heat recovery steam generator
HTF	Heat transfer fluid
HV	Hysteresis value
I	Integral controller
IGCC	Integrated gasification combined cycle
IDF	Induced draft fan
IP	Intermediate pressure
IPBPCV	Intermediate-pressure bypass control valve
IPMSCV	Intermediate-pressure main steam control valve
ISCC	Integrated solar combined-cycle power plant
JModelica	In-house process simulation programme
KTDG	Kinetic theory of dense gases
KTGF	Kinetic theory of granular fluids
LBM	Lattice Boltzmann method
LCOE	Levelised costs of energy
LES	Large eddy simulation
LFO	Light fuel oil
LHV	Lower heating value
LP	Low pressure
LPBPCV	Low-pressure bypass control valve
LPMSCV	Low-pressure main steam control valve
LV	Limit value
LU	Lower upper

MATLAB	Commercial mathematical software
MCFC	Molten carbonate fuel cell
MD	Molecular dynamics approach
MLPG	Meshless Local Petrov-Galerkin method
MODELICA	Multidomain modelling language
MPI	Message passing interface
MPICH2	Software for message passing interface
MP-PIC	Multiphase particle-in-cell
MSW	Municipal solid waste
NG	Natural gas
NPSH	Net positive suction head
ODE	Ordinary differential equation
OpenFOAM	Open-source CFD software
P	Proportional controller
P1	Radiation model
PAFC	Phosphoric acid fuel cell
PBE	Population balance equation
PD	Proportional-derivative controller
PDE	Partial differential equation
PEM	Proton exchange membrane fuel cell
PH	Preheater
PI	Proportional–integral controller
PIC	Particle-in-cell method
PID	Proportional-integral-derivative controller
PISO	Pressure-implicit with splitting of operators
PPSD	Commercial process simulation programme
POC	Post-oxidation chamber
PSIC	Particle source in cell method
PSD	Particle size distribution
PUM	Partition of unity method
PV	Photovoltaic cells
QUICK	Quadratic upwind interpolation for convective kinematic
RANS	Reynolds-averaged Navier–Stokes method
RDF	Refuse derived fuel
RELAP	Commercial process simulation programme
REF	Recirculation fan
RF	Rotary feeder
RH	Reheater
RKPM	Reproducing kernel particle method
RMS	Root mean square
SC	Steam cycle, screw conveyor
SCA	Solar collector assemble
SCE	Solar collector element
SCM	Shrinking core model
S-CO_2	Supercritical carbon dioxide

SCR	Selective catalytic reduction
Select	Selector
SFB	Stationary fluidized bed
SH	Superheater
SIMPLE	Semi-implicit method for pressure-linked equations
SIMPLEC	Semi-implicit method for pressure-linked equation consistent
SimulationX	Commercial process simulation programme
SIMULINK	Commercial mathematical software
SM	Spectral method
SNCR	Selective non-catalytic reduction
SOFC	Solid oxide fuel cell
SOR	Successive over-relaxation
SPH	Smoothed particle hydrodynamic method
ST	Steam turbine
TCP/IP	Transmission control protocol/Internet protocol
TGA	Thermogravimetric analysis
TGF	Transport gas fan
TOC	Total organic carbon
UDS	Upwind differencing scheme
VM	Vortex method
WFGD	Wet flue gas desulfurization
WS	Water/steam