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Review

Oxy-fuel combustion of pulverized fuels: Combustion fundamentals and modeling

Chungen Yin [a,*], Jinyue Yan [b,c]

[a] Department of Energy Technology, Aalborg University, 9220 Aalborg East, Denmark
[b] School of Chemical Science and Engineering, Royal Institute of Technology, Sweden
[c] School of Sustainable Development of Society and Technology, Mälardalen University, Sweden

HIGHLIGHTS

- The fundamentals underpinning oxy-fuel combustion development thoroughly reviewed.
- Oxy-fuel induced changes in combustion physics, chemistry and modeling explained.
- Generic modeling strategies for PF oxy-fuel combustion successfully proposed.
- Oxy-fuel based power generation and CCS systems and the key issues discussed.
- Research needs in oxy-fuel combustion fundamentals and their modeling identified.

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ABSTRACT

Oxy-fuel combustion of pulverized fuels (PF), as a promising technology for CO_2 capture from power plants, has gained a lot of concerns and also advanced considerable research, development and demonstration in the past years worldwide. The use of CO_2 or the mixture of CO_2 and H_2O vapor as the diluent in oxy-fuel combustion, instead of N_2 in conventional air–fuel combustion, induces significant changes to the combustion fundamentals, because of the great differences in the physical properties and chemical effects of the different diluents. Therefore, some fundamental issues and technological challenges need to be properly addressed to develop oxy-fuel combustion into an enabled technology. Computational Fluid Dynamics (CFD) modeling, which has been proven to be a very useful and cost-effective tool in research and development of conventional air–fuel combustion, is expected to play a similarly vital role in future development of oxy-fuel combustion technology. The paper presents a state-of-the-art review and an in-depth discussion of PF oxy-fuel combustion fundamentals and their modeling, which underpin the development of this promising technology. The focus is placed on the key issues in combustion physics (e.g., turbulent gas–solid flow, heat and mass transfer) and combustion chemistry (e.g., pyrolysis, gas phase combustion and char reactions), mainly on how they are affected in oxy-fuel conditions and how they are modeled and implemented into CFD simulations. The system performance of PF oxy-fuel combustion is also reviewed. Finally, the current status of PF oxy-fuel combustion fundamentals and modeling is concluded and the research needs in these regards are suggested.

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* Corresponding author. Tel.: +45 30622577; fax: +45 98151411.
E-mail address: chy@et.aau.dk (C. Yin).

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Nomenclature

A	frequency factor in rate coefficient in Arrhenius form (s^{-1})
A_{BET}	particle BET surface area (m^2/kg)
A_p	particle projected area (m^2)
$A_{p,i}$	projected area of group *i* particles (m^2)
A_{ps}	particle surface area (m^2)
$b_{\varepsilon,i,j}$	emissivity gas temperature polynomial coefficients in WSGGM (–)
c_s	concentration of PF particles (kg/m^3)
C_D	drag coefficient (–)
C_p	specific heat (J/(kg K))
d_p	particle size (m)
$\frac{dm_p}{dt}$	conversion rate of particle in different sub-processes (kg/s)
D	pipe diameter (m)
D_g	mass diffusivity (m^2/s)
E	activation energy in rate coefficient in Arrhenius form (J/kmol)
$f_{p,i}$	scattering factor of group *i* particles (–)
$f_{w,0}$	initial moisture fraction (–)
$g, \mathbf{g}$	gravitational acceleration (m/s^2)
h_M	convective mass transfer coefficients (m/s)
h_T	convective heat transfer coefficients ($W/(m^2\,K)$)
$I(\vec{r}, \hat{s})$	radiative intensity at position $\vec{r}$ in direction $\hat{s}$ ($W/(m^2\,sr)$)
k	kinetic rate (s^{-1})
k_g	gas thermal conductivity (W/(m K))
k_i	absorption coefficient of *i*-th gray gas in WSGGM (1/(atm m))
L	domain-based beam length (m)
L_c	characteristic length (m)
m_a	particle ash content (kg)
m_p	particle mass (kg)
$m_{p,0}$	initial particle mass at injection (kg)
$m_v(t)$	mass of volatile yield up to time *t* (kg)
$\mathrm{MW_N}$	molecular weight of N (kg/kmol)
$\mathrm{MW_{NO}}$	molecular weight of NO (kg/kmol)
n_i	number density of group *i* particles ($1/m^3$)
Nu	Nusselt number (–)
P	sum of partial pressures of the participating gases (atm)
P_{atm}	local gas pressure (atm)
P_{pa}	local gas pressure (Pa)
Pr	Prandtl number (–)
q_r	radiative flux (W/m^2)
$\Re$	conversion rate (s^{-1})
Re	Reynolds number (–)
Re_p	particle Reynolds number, $Re_p = \rho_g \lvert\mathbf{u} - \mathbf{v}\rvert d_p/\mu_g$ (–)
R_u	universal gas constant (8315) (J/(kmol K))
s	path length (m)
S_c	char burnout rate (kg/s)
Sc	Schmidt number (–)
Sh	Sherwood number (–)
S_{NO}	NO source term ($kg/(m^3\,s)$)
t	time (s)
T	temperature (K)
T_g	local gas temperature (K)
$T_{p,i}$	temperature of group *i* particles (K)
$\mathbf{u}$	gas velocity (m/s)
u_{min}	the minimum (or saltation) velocity (m/s)
U_C	fraction of unburnt char, $U_C = \frac{\text{mass of char in particle}}{\text{mass of char in feed particle}}$ (–)
$U_{VM,C}$	fraction of unburnt combustibles, $U_{VM,C} = \frac{\text{mass of volatiles and char in particle}}{\text{mass of volatiles and char in feed particle}}$ (–)
$\mathbf{v}$	particle velocity (m/s)
V	cell volume (m^3)
V_p	particle volume (m^3)
X	mole fraction (–)
X_{NO}	mole fraction of NO (–)
$Y_{\mathrm{N,char}}$	mass fraction of nitrogen in char (–)

Greek letters

α	local gas absorption coefficient (m^{-1})
α_1, α_2	two yield factors (–)
α_p	equivalent particle absorption coefficient (m^{-1})
ΔH	heat effects (J/kg)
ε	total emissivity of local gas mixture (–)
ε_p	particle emissivity (–)
$\varepsilon_{p,i}$	emissivity of group *i* particles (–)
η	conversion factor (–)
θ_R	radiation temperature (K)
μ_g	air or gas dynamic viscosity (kg/(m s))
μ_t	turbulent viscosity (kg/(m s))
ρ_g	air or gas density (kg/m^3)
ρ_p	particle density (kg/m^3)
σ	Stefan–Boltzmann constant (5.67×10^{-8}) ($W/(m^2\,K^4)$)
σ_p	equivalent particle scattering coefficient (m^{-1})
τ_v	particle momentum response time, $\tau_v = \rho_p d_p^2/(18\mu_g)$ (m)
ϕ	phase function (–)
Ω, Ω'	solid angle (sr)

Abbreviations

CCS	carbon capture and storage
CFD	Computational Fluid Dynamics
CPD	Chemical Percolation Devolatilization
CTF	combustion test facility
DO	discrete ordinates (radiation model)
DTF	drop tube furnace
DTR	drop tube reactor
DTRM	discrete transfer radiation model
EBU	eddy-breakup
ED	Eddy Dissipation
EDC	Eddy Dissipation Concept
EFR	entrained flow reactor
EWBM	exponential wide band model
FG-DVC	Functional Group – Depolymerisation Vaporisation Cross-linking
FR/ED	Finite Rate/Eddy Dissipation
FSK	full spectrum *k*-distribution
JL 4-step	Jones and Lindstedt 4-step
LES	large eddy simulation
PF	pulverized fuel
RANS	Reynolds-Averaged Navier–Stokes
RFG	recycled flue gas
RTE	radiative transfer equation
TGA	thermogravimetric analysis
UDF	user-defined function
VM	volatile matters
WD 2-step	Westbrook and Dryer 2-step
WSGGM	weighted sum of gray gases model