ULB UNIVERSITÉ LIBRE DE BRUXELLES

OPTIMIZATION OF A DRY LOW NO_X MICROMIX COMBUSTOR FOR AN INDUSTRIAL GAS TURBINE USING HYDROGEN-RICH SYNGAS FUEL

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Abstract

Environmentally friendly and efficiently produced energy from sustainable and renewable resources is of great importance. Carbon dioxide (CO_2) and nitric oxides (NO_x) are the main emissions of air-breathing gas turbines in power plants. Gas turbines of the power generation industry are normally fueled with liquid fuels, natural gas or syngas in changing qualities. Syngas can be produced by gasification processes in IGCC power plants and consist of varying percentages of the main fractions hydrogen (H_2) and carbon monoxide (CO). CO_2 emissions can be reduced by a decrease of the CO-share and an increase of the hydrogen-share in the syngas fuel, and by using pre-combustion carbon capture and sequestration (CCS) technology. For low NO_x, current gas turbine combustion chamber technologies require diluents, a rather low H_2 content and modifications of the combustor hardware. A feasible solution for low NO_x hydrogen and syngas combustion in gas turbines is the Micromix principle developed at Aachen University of Applied Sciences. The goal of this doctoral thesis is the research on a Micromix combustor with increased power densities fueled with hydrogen-rich syngas with about 90% by volume hydrogen, and going up to 100% hydrogen in the fuel. Test burner experiments are used to characterize the combustion and emission properties of a multitude of key drivers. Based on this optimization with a variety of scaled model test burners, a prototype dual-fuel hydrogen/syngas Micromix combustor is designed and integrated into the annular combustion chamber of an industrial gas turbine. In the gas turbine, the performance characteristics of the prototype-combustor are investigated under real operational conditions with hydrogen-rich syngas and pure hydrogen.

Résumé

L'énergie écologique et efficiente produite à partir de ressources durables et renouvelables est d'une grande importance. Le CO_2 et les NO_x sont les principales émissions des turbines à gaz dans les centrales électriques. Les turbines à gaz de l'industrie de la production d'énergie sont normalement alimentées en combustibles liquides, gaz naturel ou gaz de synthèse (syngas) dans des conditions changeantes. Le syngas peut être produit par des procédés de gazéification dans les centrales électriques IGCC et se compose de pourcentages variables de fractions de H_2 et de CO. Les émissions de CO_2 peuvent être réduites par une diminution de la part du CO et une augmentation de la part d'hydrogène dans le syngas ou en utilisant la technologie de capture et de séquestration du carbone (CCS) de précombustion. Pour les NO_x faibles, les technologies actuelles de la chambre de combustion des turbines à gaz nécessitent des diluants, une faible teneur en H_2 et des modifications du matériel de la chambre de combustion. Une solution réalisable pour la combustion de syngas et d'hydrogène à faible emissions en NO_x dans les turbines à gaz est le principe de Micromix (MMX) développé à l'Université des Sciences Appliquées d'Aachen. L'objectif de cette thèse de doctorat est la recherche sur une chambre de combustion Micromix avec des densités d'énergie accrues pour de syngas riche en H_2 avec environ 90% d´hydrogène et 100% de H_2. Les travaux sur les brûleurs de test sont utilisés pour caractériser les propriétés de combustion et d'émission d'une multitude de facteurs clés. Sur la base de cette optimisation, une chambre de combustion Micromix à hydrogène/syngas à hydrogène double à grande échelle est créée et intégrée dans la chambre de combustion annulaire d'une turbine à gaz industrielle et ses performances de démarrage et de changement de charge sont étudiées dans des conditions réelles de fonctionnement de turbines à gaz en syngas riche en hydrogène et hydrogène seulement.

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Nomenclature

Abbreviations

3D	three-dimensional
AcUAS	Aachen University of Applied Sciences
ABB	Asea Brown Boveri
AEV	Advanced Environmentally-friendly V-shaped burner
AGP	air guiding panel
APU	auxiliary power unit
BBC	Brown Boveri Company
C	carbon
C_2H_6S	dimethyl sulfide
$C_2H_6S_2$	dimethyl disulfide
CCP	combined cycle plant
CCS	carbon capture and storage
CCU	carbon capture and use
CFD	computational fluid dynamics
CH	hydrocarbons
CH_4	methane
CO	carbon monoxide
CO_2	carbon dioxide
COS	carbonyl sulfide
const.	constant
CS_2	carbon sulfide
DLE	dry low emissions
DLN	dry low NO_x
DP	design point
EBU	Eddy-Break-Up
ECS	environmental control supply
EGT	exhaust gas temperature

EQHHPP	Euro-Québec-Hydro-Hydrogen-Pilot-Project
EU	European Union
EV	Environmentally-friendly V-shaped (burner)
FLOX	Flameless Oxidation
H-EBU	hybrid-EBU
H*	hydrogen radical
H_2	hydrogen
H_2O	water
H_2S	hydrogen sulfide
H_2SO_4	sulfuric acid
HO_2	hydroperoxyl
IGCC	integrated gasification combined cycle
IGV	inlet guide vane
JICF	jet in crossflow
LHV	lower heating value
MBtu	Mega ($1 \cdot 10^6$) British Thermal Units
MES	main engine start
MILD	Moderate or Intense Low Oxygen Dilution
MMX	Micromix
MT	multi-tube
N_2	nitrogen
N_2H_3	ammonia
N_2O	nitrous oxide
NG	natural gas
NO	nitrogen monoxide
NO_2	nitrogen dioxide
NO_x	nitric oxides
O*	oxygen radical
O_2	oxygen
O_3	ozone

OH*	hydroxyl radical
OH-PLIF	hydroxyl planar laser-induced fluorescence
PD_n	normalized power density
ppm	parts per million
r	Arrhenius-formulation
RANS	Reynolds-averaged Navier–Stokes equation
rpm	revolutions per minute
R-SH	mercaptans
SAR	stoichiometric air requirement
SG	syngas
SG 90/10	customized SG-mixture for testing
SO_2	sulfur dioxide
SO_3	sulfur trioxide
TBC	thermal barrier coating
TCD	thermal conductivity detector
UHC	unburned hydrocarbons
ULB	Université Libre de Bruxelles
VECB	Versatile Engine Control Box
VOC	volatile organic compounds

Greek Notations

α	alpha – constant	[-]
β	beta – constant	[-]
γ	gamma – constant	[-]
Δ	delta – difference	[-]
η_A	eta - combustion efficiency	[-]
κ	kappa - isentropic exponent	[-]
λ	lambda – air fuel equivalence ratio	[-]

λ_{DP}	air fuel equivalence ratio at design point	[-]
Φ	phi – fuel air equivalence ratio	[-]
Φ_{DP}	fuel air equivalence ratio at design point	[-]
Ψ_{CO}	psi – substance amount of CO	[ppm]
Ψ_{H2}	psi – substance amount of hydrogen	[ppm]
Ψ_j	psi – substance amount of component j	[ppm]
Ψ_{NO}	psi – substance amount of NO	[ppm]
Ψ_{NO2}	psi – substance amount of NO_2	[ppm]
Ψ_{NOx}	psi – substance amount of NO_x	[ppm]
ρ_{air}	rho – density of air	$\left[\frac{kg}{m^3}\right]$
ρ_{fuel}	rho – density of fuel	$\left[\frac{kg}{m^3}\right]$
θ	theta – air load factor	$\left[\frac{(bar\cdot m)^{1.75}\cdot s}{kg}\right]$

Latin Notations

A_{ref}	reference area	$[m^2]$
ALF	air load factor	$\left[\frac{(bar\cdot m)^{1.75}\cdot s}{kg}\right]$
b_{ref}	reference width	[m]
BR	blockage ratio	[-]
BR_{AGP}	blockage ratio of air guiding panel	[-]
BR_{Seg}	blockage ratio of burner segment	[-]
BRDR	blockage ratio dimension ratio	[-]
c	velocity	$\left[\frac{m}{s}\right]$
c_{air}	air velocity	$\left[\frac{m}{s}\right]$
c_{fuel}	fuel velocity	$\left[\frac{m}{s}\right]$
c_p	specific heat capacity	$\left[\frac{kJ}{kg\cdot K}\right]$

CO	carbon monoxide	$\left[\frac{mg}{m^3}\right]$, [ppm]
CO_2	carbon dioxide	$\left[\frac{mg}{m^3}\right]$, [ppm]
d_{fuel}	injector nozzle diameter	[m]
d_{AGP}	inner dimensions of air guiding panel	[m]
D_{AGP}	outer dimensions of air guiding panel	[m]
d_{Seg}	inner dimensions of burner segment	[m]
D_{Seg}	outer dimensions of burner segment	[m]
EGT	exhaust gas temperature	[K]
EI	emissions index	$\left[\frac{mg}{m^3}\right]$
g_{CO}	mass related share of carbon monoxide	[-]
g_{H2}	mass related share of hydrogen	[-]
H_0	relative ambient air humidity	[%]
H_2	hydrogen	$\left[\frac{mg}{m^3}\right]$,[ppm]
h_{gate}	height of air gate	[m]
h_{ref}	reference height	[m]
J	momentum ratio	[-]
J_{DP}	momentum ratio at design point	[-]
J_{max}	maximum momentum ratio	[-]
LHV	lower heating value	$\left[\frac{MJ}{kg}\right]$, $\left[\frac{MJ}{m^3}\right]$
$\dot{m}$	mass flow	$\left[\frac{kg}{s}\right]$
$\dot{m}_{air}$	mass flow of air	$\left[\frac{kg}{s}\right]$
$\dot{m}_{CO}$	mass flow of carbon monoxide	$\left[\frac{kg}{s}\right]$
$\dot{m}_{fuel}$	mass flow of fuel	$\left[\frac{kg}{s}\right]$
$\dot{m}_{H2}$	mass flow of hydrogen	$\left[\frac{kg}{s}\right]$
$\dot{m}_{Kerosene}$	mass flow of kerosene (Jet A-1)	$\left[\frac{kg}{s}\right]$
M	molar mass	$\left[\frac{kg}{kmol}\right]$

n_{fuel}	number of fuel injector nozzles	[-]
N_2	nitrogen	[%]
NO	nitrogen monoxide	$\left[\frac{mg}{m^3}\right]$, [ppm]
NO_2	nitrogen dioxide	$\left[\frac{mg}{m^3}\right]$, [ppm]
NO_x	nitric oxides	$\left[\frac{mg}{m^3}\right]$, [ppm]
O_2	oxygen	[%]
p_0	ambient pressure	[bar]
p_1	pressure at air inlet	[bar]
p_2	pressure at compressor inlet	[bar]
p_3	combustor inlet pressure	[bar]
p_5	pressure after last turbine stage	[bar]
p_{fuel}	fuel pressure	[bar]
p_{oil}	oil pressure	[bar]
p_{ref}	reference pressure	[bar]
p_{st}	static pressure	[bar]
PD_n	normalized power density	$\left[\frac{MJ}{m^2 \cdot bar}\right]$
$\dot{Q}$	heat flow rate	$\left[\frac{MJ}{s}\right]$
$\dot{Q}_{H2}$	heat flow rate of hydrogen	$\left[\frac{MJ}{s}\right]$
$\dot{Q}_{Kerosene}$	heat flow rate of kerosene (Jet A-1)	$\left[\frac{MJ}{s}\right]$
$\dot{Q}_{SG}$	heat flow rate of syngas (SG 90/10)	$\left[\frac{MJ}{s}\right]$
r	radius	[m]
R_{air}	specific gas constant of air	$\left[\frac{J}{kg \cdot K}\right]$, $\left[\frac{J}{kmol \cdot K}\right]$
R_{fuel}	specific gas constant of fuel	$\left[\frac{J}{kg \cdot K}\right]$, $\left[\frac{J}{kmol \cdot K}\right]$
R_M	general gas constant	$\left[\frac{J}{kg \cdot K}\right]$, $\left[\frac{J}{kmol \cdot K}\right]$
Re	Reynolds Number	[-]
s	distance between injector nozzles	[m]

s_n	normalized distance between injectors	[-]
SAR	stoichiometric air requirement	[-]
T	temperature	[K]
T_0	ambient temperature	[K]
T_1	temperature at air inlet	[K]
T_3	combustor inlet temperature	[K]
T_4	combustor outlet temperature	[K]
T_{amb}	ambient temperature	[K]
T_{fuel}	fuel temperature	[K]
T_{ref}	reference temperature	[K]
T_t	total temperature	[K]
WI	Wobbe Index	$\left[\frac{MJ}{kg}\right], \left[\frac{MJ}{m^3}\right]$
WI_i	inferior Wobbe Index	$\left[\frac{MJ}{kg}\right], \left[\frac{MJ}{m^3}\right]$
y	injection depth of fuel jet in air cross-flow	[m]
y_{crit}	critical injection depth	[m]
y_{DP}	injection depth at design point	[m]
y_{max}	maximum injection depth	[m]
y_n	normalized injection depth	[m]
$(\Delta p/p)$	pressure loss	[-]

Note: emissions are usually given in [ppm] or $\left[\frac{mg}{m^3}\right]$. The conversion calculations between those units are given in the appendix. To allow the comparison of data from mentioned publications that usually use [ppm], the emission measurements in this thesis are given in [ppm] or [%]. For selected points of interest, the corresponding value in $\left[\frac{mg}{m^3}\right]$ is added in the text.

Subscripts

0	ambient conditions
1	station 1 of the gas turbine: air inlet
2	station 2 of the gas turbine: compressor inlet
3	station 3 of the gas turbine: combustor inlet
4	station 4 of the gas turbine: combustor outlet
5	station 5 of the gas turbine: turbine outlet
ad	adiabatic
AGP	air guiding panel
air	air related parameters in general
amb	ambient conditions
APU	related to auxiliary power unit
CO	carbon monoxide related parameters in general
crit	critical
DP	design point
dyn	dynamic
ECS	related to ECS-mode
eff	effective
FMU	fuel metering unit
fuel	fuel related parameters in general
gate	parameters related to the air gate in an air guiding panel
H_2	hydrogen related parameters in general
i	inferior
j	general numerical index
Kerosene	kerosene (Jet A-1) related parameters in general
kg	mass related
max	maximum
MES	related to MES-mode
min	minimum
MMX	related to Micromix in general

n	normalized
NO	nitric oxide related parameters in general
NO2	nitrogen dioxide related parameters in general
NO_x	nitrogen oxides related parameters in general
oil	oil
ref	reference
Seg	related to the MMX burner segment
SG	syngas related parameters in general
st	static
t	total
Test-Rig	related to atmospheric test rig