A COMPARATIVE STUDY OF NATURAL GAS AND BIOGAS COMBUSTION IN A SWIRLING FLOW GAS TURBINE COMBUSTOR

BY

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ABSTRACT

In this study, the non-premixed combustion of a traditional fuel- natural gas, and an alternative fuel- biogas, in a swirl-stabilized gas turbine combustor are simulated. The combustion results are analyzed and compared to evaluate the viability of the alternative fuel, biogas, for use in industrial gas turbine combustors. A comprehensive and exhaustive literature review on topics relating the current work is carried out. Two benchmark experimental cases of swirl-stabilized non-reacting and reacting flows are simulated in 3D and validated against the experiments to select the proper numerical, physical and combustion modeling of such complex flows. A swirling gas turbine combustor is designed to carry out non-premixed combustion of the fuels, using a well-known and recognized combustor design methodology and empirical equations. Investigating the existing literatures, the suitable compositions and stoichiometric air-fuel ratio of the gases are determined. Unlike the combustion works in existing literature, the outer annulus region (between the liner and casing) is considered in the computational domain to obtain more realistic results on the flow physics and chemical reactions during combustion. As the swirling flow is 3D in nature, a full 3D grid is generated to address complex flow physics and turbulent-chemistry interactions. Afterward, the combustion of both gases is numerically simulated, and the combustion performance is evaluated based on the design objectives: combustion efficiency, pollutant CO and NO_x emission, Merit Function, and temperature uniformity of the exhaust gases at the combustor exit (Pattern Factor). The effects of two design parameters, namely: swirl number and fuel injector radius, in achieving best performance in design objectives are examined. It was found that, typically, a combination of higher fuel injector radius (or lower fuel velocity) and higher swirl number (2.0 in current study) produces best performance in achieving the design objectives. The swirling flow should be dominant over the incoming fuel flow to facilitate better and finer mixing of air and fuel, which typically contributes to a better combustion efficiency, pattern factor, and low pollutant emission. It is important to point out that, the empirical swirl number (0.9), achieved through an empirical formulation, does not provide the best performance in any of the design objective for both gases. Lastly, the comparison of the combustion performances of both gases revealed that, despite possessing much lower methane and hence lower heating value (LHV), biogas of a specific composition demonstrates an equal combustion performance to natural gas, although at the expense of higher pollutant emission. Therefore, biogas can potentially be utilized as an alternative fuel in industrial gas turbine combustors and methods for reducing pollutant emission can be devised.

خلاصة البحث

في هذه الدراسة، تمت محاكاة الاحتراق غير الممزوج مسبقًا لوقود الغاز الطبيعي التقليدي، وللغاز الحيوي البديل ، في احتراق التوربينات الغازية المستقرة. تم تحليل نتائج الاحتراق ومقارنتها لتقييم جدوى وقود الغاز الحيوي البديل ، لاستخدامه في احتراق التوربينات الغازية الصناعية. تمت إجراء مراجعة كاملة وشاملة لكل الدراسات السابقة حول الموضوعات المتعلقة بالعمل الحالي. يتم محاكاة حالتين تجريبيتين معياريتين للتدفقات غير المتفاعلة والمتفاعلة المستقرة على شكل دوامة في صورة ثلاثية الأبعاد والتحقق من صحتها مقابل التجارب لتحديد النمذجة العددية والفيزيائية والاحتراق المناسبة لمثل هذه التدفقات المعقدة. تم تصميم جهاز احتراق التوربينات الغازية الدوامة لإجراء احتراق غير مخلوط مسبقًا للوقود ، باستخدام منهجية تصميم غرفة الاحتراق والمعادلات التجريبية المعروفة والمعترف بها. بالتحقيق في الدراسات السابقة الموجودة ، فإن التركيبات المناسبة ونسبة الهواء إلى الوقود المتكافئ للغازات تم تحديدها. على عكس أعمال الاحتراق الموجودة في الدراسات السابقة ، يتم اعتبار منطقة الحلقة الخارجية (بين البطانة والغلاف) في المجال الحسابي للحصول على نتائج أكثر واقعية في فيزياء التدفق والتفاعلات الكيميائية أثناء الاحتراق. نظرًا لأن التدفق الدوامي ثلاثي الأبعاد بطبيعته ، يتم إنشاء شبكة ثلاثية الأبعاد كاملة لمعالجة فيزياء التدفق المعقدة والتفاعلات الكيميائية المضطربة. بعد ذلك ، يتم محاكاة احتراق كلا الغازين عدديًا ، ويتم تقييم أداء الاحتراق بناءً على أهداف التصميم: كفاءة الاحتراق ، وانبعاثات ثاني أكسيد الكربون وأكاسيد النيتروجين ، ووظيفة الاستحقاق ، وتوحيد درجة حرارة غازات العادم عند مخرج الاحتراق (عامل النمط) .يتم فحص تأثير اثنين من معاملات التصميم ، وهما: رقم الدوران ونصف قطر حاقن الوقود ، في تحقيق أفضل أداء في أهداف التصميم. وقد وجد أنه ، بشكل نموذجي ، مزيج من نصف قطر حاقن الوقود الأعلى (أو سرعة وقود أقل) ورقم دوامة أعلى (2.0 في الدراسة الحالية) ينتج أفضل أداء في تحقيق أهداف التصميم. يجب أن يكون التدفق الدوامي هو المسيطر على تدفق الوقود الوارد لتسهيل الخلط الأفضل والأكثر دقة بين الهواء والوقود ، والذي يساهم عادةً في كفاءة احتراق أفضل ، وعامل نمط أفضل ، وانبعاثات منخفضة للملوثات. من المهم الإشارة إلى أن رقم الدوامة التجريبية (0.9) ، الذي تم تحقيقه من خلال صياغة تجريبية، لا يوفر أفضل أداء في أي من أهداف التصميم لكلا الغازين. أخيرًا ، كشفت المقارنة بين أداء الاحتراق لكلا الغازين أنه على الرغم من احتوائه على كمية أقل بكثير من الميثان وبالتالي قيمة تسخين أقل (LHV)، فإن الغاز الحيوي لتركيبة معينة يوضح أداء احتراق متساوٍ للغاز الطبيعي ، على الرغم من احتوائه على انبعاثات ملوثة أعلى.

لذلك ، يمكن استخدام الغاز الحيوي كوقود بديل في محارق التوربينات الغازية الصناعية ويمكن إبتكار طرق لتقليل انبعاث الملوثات.

APPROVAL PAGE

I certify that I have supervised and read this study and that in my opinion; it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a thesis for the degree of Master of Science (Mechanical Engineering).

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DECLARATION

I hereby declare that this thesis is the result of my own investigations, expect where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at IIUM or other institutions.

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To Sümeyye

For her empathy, love, and her faith. Because she always understood.

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All praise is due to Allah. We praise Him, seek His help, ask His forgiveness, and we repent unto Him. We seek refuge in Allah from the evils of ourselves and our bad actions. Whomever Allah guides none can lead astray, and whomever He leads astray has no one to guide him.

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LIST OF SYMBOLS

W_j	Air stream through the jet hole.
W_s	Bulk Axial velocity of air stream through the annulus.
U_s	Bulk Tangential velocity of air stream through the annulus.
W_e	Co-flow velocity of the secondary air stream generated in the wind tunnel.
S_g	Geometric swirl number
S	Swirl number
x, y, z	Cartesian coordinates
r	Radial axis of polar coordinates
k	Turbulent kinetic energy
ϵ	Turbulent dissipation rate
ω	Specific dissipation rate
R	Characteristic length
W	Mean axial component of velocity
U	Mean tangential component of velocity
u_i	Velocity component in the x_i direction
i, j, k	Unit vectors in the direction of the x, y, and z axes
ρ	Density
τ_{ij}^{t}	Residual stress tensor
p	Pressure
μ	Dynamic viscosity
μ_t	Eddy viscosity
D	Bluff body diameter
R_j	Jet hole radius
z	Axial position/distance
f	Mean mixture fraction
f'^2	Mixture fraction variance
χ_{st}	Mean scalar dissipation
L_S	Subgrid length scale
ΔP_{3-4}	Total pressure-drop across the combustor
q_{ref}	Reference dynamic pressure at the maximum cross-sectional area
A_{ref}	Reference area
R_a	Universal gas constant
D_{ref}	Reference diameter
A_L	Liner area
D_L	Liner diameter
A_{an}	Annulus area
L_{PZ}	Primary zone length
L_{SZ}	Secondary zone length
L_{DZ}	Dilution zone length
L_{RZ}	Recirculation zone length
$\Delta P_{3-4}/q_{ref}$	Pressure-loss factor
T_{max}	Maximum combustor outlet temperature

T_4	Mean combustor outlet temperature
$\dot{m}_3$	Inlet air mass flow rate
P_3	Inlet pressure
T_3	Inlet air temperature
D_3	Diameter of compressor outlet area
R_3	Radius of compressor outlet area
$\dot{m}_f$	Inlet fuel mass flow rate
T_f	Inlet fuel temperature
$\dot{m}_S$	Air-flow rate through snout
$\dot{m}_{SW}$	Air-flow rate through swirler
$\dot{m}_{dome}$	Air-flow rate through dome
$\dot{m}_{an}$	Air-flow rate through annulus
$\dot{m}_h$	Air-flow rate through holes
$\dot{m}_{h,PZ}$	Air-flow rate through primary holes
$\dot{m}_{h,SZ}$	Air-flow rate through secondary holes
$\dot{m}_{cool}$	Air-flow rate through cooling slots
$\dot{m}_{h,DZ}$	Air-flow rate through dilution holes
A_o	Snout outer area
D_o	Snout outer diameter
R_o	Snout outer radius
ψ	Divergence angle of the diffuser
L_{dif}	Diffuser length
A_S	Snout area
D_S	Snout diameter
$D_{O,SW}$	Swirler outer diameter
$D_{I,SW}$	Swirler inner diameter
β_{SW}	Vane angle of blades
θ	Inclination angle of the dome
L_{dome}	Dome length
s	Cooling slot height
t	Cooling slot lip thickness
t_w	Flame tube wall thickness
β	Bleed ratio
$C_{d,h}$	Hole discharge coefficient
A_h	Total hole area
D_h	Hole diameter
$\Delta P_h/P_3$	Pressure-loss through a hole
α	Orifice area ratio
K	Hole pressure loss factor
δ	Momentum loss factor
N_h	Number of holes for each combustion zone
$D_{h,PZ}$	Diameter of primary holes
$D_{h,SZ}$	Diameter of secondary holes
$D_{h,DZ}$	Diameter of dilution holes
$D_{h,dome}$	Diameter of dilution holes at dome
AF_{st}	Stoichiometric air-fuel ratio of fuel
AF_{excess}	Air-fuel ratio at primary zone (with approximately 10% excess air)