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

BY

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A thesis submitted in fulfilment of the requirement for the degree of Master of Science (Mechanical Engineering)

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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 NOx 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، تم تطبيق الاحتراس غير الممزوج مسبقًا لوقود الغاز الطبيعي التقليدي، ولغاز الحيوي البديل، واحتراق التوربينات الغازية المستقرة. تم تحليل نتائج الاحتراس ومقارنتها لتقديم جدول وقود للغاز الحيوي البديل، لاستخدامه في احتراق التوربينات الغازية الصناعية. تم إجراء مراجعة كاملة وشملة لكل الدراسات السابقة حول الموضوعات المتعلقة بالعمل الحالي. يتم محاكاة حالتين تجريبيتين معيارتين للتدفقات غير المتفاعلة والتفاعل المستقرة على شكل دورة في صورة ثلاثية الأبعاد والتحقيق من صحتها مقابل التجربة لتحقيق النسب العامة والتفاعلية والاحتراس المناسب لمثل هذه التدفقات المعقدة. تم تصميم جهاز احتراق التوربينات الغازية الدوامة لإجراء احتراق غير مخلوط مسبقًا للوقود، باستخدام منهجية تصميم غرفة الاحتراق والمعادلات الجبرية المعروفة ومخطط مرجعة. بالتحقيق في الدراسات السابقة، فإن التدفق الدوامي هو أفضل الصيغ للوقود بالنسبة لمثل هذه التدفقات المعقدة. يتم إجراء مراجعة شاملة لكل الدراسات السابقة حول الموضوعات المتعلقة بالعمل الحالي. يتم اعتبار منطقة الدوامة الخارجية (بين البطانة والغلاف) في الحالة الحسابية للحصول على نتائج أكثر واقعية في دراسة التدفق والتفاعلات الكيميائية أثناء الاحتراق. نظرًا لأن التدفق الدوامي ثلاثي الأبعاد بطيء، يتم إنشاء شبكة ثلاثية الأبعاد كاملة لمعالجة فيزياء التدفق المعقدة والتفاعلات الكيميائية المضطربة. بعد ذلك، يتم محاكاة احتراق كلا الغازين على شكل دورة احتراق عميقة، وتم تقييم أداء احتراق النوعان على أهداف التصميم: كفاءة الاحتراق، وانبعاثات ثاني أكسيد الكربون، وكربون الدفيئة، ووظيفة الاستحقاق، وتوحيد درجة حرارة غازات الدوامة عند مخرج الاحتراق (عامل النمط). يتم تحديد تأثير الغازين من معاملات التصميم، وهما: رقم الدوران ونصف قطر حاقن الوقود، في تحقيق أفضل أداء في أهداف التصميم. وقد وجد أنه، بشكل متزنجي، مزيج من نصف قطر حافل 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، ومواد وقفة أفضل، وانبعاثات منخفضة للملوثات. من المهم الإشارة إلى أن رقم الدوامة التجريبية (0.9) الذي تم تقديره من خلال صيغة تجريبية، لا يوفر أفضل أداء في أي من أهداف التصميم للكل الغازين. أخيرًا، كشفت المقارنة بين احتراق كلا الاحتراس لكلا الغازين أنه على الرغم من احتوائه على كمية أقل بكثير من الميثان وبالتالي قيمة تستئنف أقل (LHV)، فإن الغاز الحيوي لتكوين 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 لتقليص انبعاث الملوثات.
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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Sany Izan Ihsan  
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DECLARATION

I hereby declare that this thesis is the result of my own investigations, except 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.

Tariq Md Ridwanur Rahman

Signature:…………………… Date:…………………………… 17/8/2020
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To Sümayye

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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Figure 5.33  Combustion efficiency against swirl number. Left: findings in current investigation. Right: Results of Torkzadeh et al. (2016)

Figure 5.34  Merit Function for pollutant emissions against swirl number. Left: findings in current investigation. Right: Results of Torkzadeh et al. (2016)

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Figure 5.55  CO emission at the combustor exit against swirl number for natural gas (NG) and biogas (BG) combustions, using different fuel injectors.
**LIST OF SYMBOLS**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W_j$</td>
<td>Air stream through the jet hole.</td>
</tr>
<tr>
<td>$W_s$</td>
<td>Bulk Axial velocity of air stream through the annulus.</td>
</tr>
<tr>
<td>$U_s$</td>
<td>Bulk Tangential velocity of air stream through the annulus.</td>
</tr>
<tr>
<td>$W_e$</td>
<td>Co-flow velocity of the secondary air stream generated in the wind tunnel.</td>
</tr>
<tr>
<td>$S_g$</td>
<td>Geometric swirl number</td>
</tr>
<tr>
<td>$S$</td>
<td>Swirl number</td>
</tr>
<tr>
<td>$x, y, z$</td>
<td>Cartesian coordinates</td>
</tr>
<tr>
<td>$r$</td>
<td>Radial axis of polar coordinates</td>
</tr>
<tr>
<td>$k$</td>
<td>Turbulent kinetic energy</td>
</tr>
<tr>
<td>$\epsilon$</td>
<td>Turbulent dissipation rate</td>
</tr>
<tr>
<td>$\omega$</td>
<td>Specific dissipation rate</td>
</tr>
<tr>
<td>$R$</td>
<td>Characteristic length</td>
</tr>
<tr>
<td>$W$</td>
<td>Mean axial component of velocity</td>
</tr>
<tr>
<td>$U$</td>
<td>Mean tangential component of velocity</td>
</tr>
<tr>
<td>$u_i$</td>
<td>Velocity component in the $x_i$ direction</td>
</tr>
<tr>
<td>$i, j, k$</td>
<td>Unit vectors in the direction of the $x, y,$ and $z$ axes</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Density</td>
</tr>
<tr>
<td>$\tau_{ij}^*$</td>
<td>Residual stress tensor</td>
</tr>
<tr>
<td>$p$</td>
<td>Pressure</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Dynamic viscosity</td>
</tr>
<tr>
<td>$\mu_t$</td>
<td>Eddy viscosity</td>
</tr>
<tr>
<td>$D$</td>
<td>Bluff body diameter</td>
</tr>
<tr>
<td>$R_j$</td>
<td>Jet hole radius</td>
</tr>
<tr>
<td>$z$</td>
<td>Axial position/distance</td>
</tr>
<tr>
<td>$f$</td>
<td>Mean mixture fraction</td>
</tr>
<tr>
<td>$f'^2$</td>
<td>Mixture fraction variance</td>
</tr>
<tr>
<td>$\chi_{st}$</td>
<td>Mean scalar dissipation</td>
</tr>
<tr>
<td>$L_S$</td>
<td>Subgrid length scale</td>
</tr>
<tr>
<td>$\Delta P_{3-4}$</td>
<td>Total pressure-drop across the combustor</td>
</tr>
<tr>
<td>$q_{ref}$</td>
<td>Reference dynamic pressure at the maximum cross-sectional area</td>
</tr>
<tr>
<td>$A_{ref}$</td>
<td>Reference area</td>
</tr>
<tr>
<td>$R_a$</td>
<td>Universal gas constant</td>
</tr>
<tr>
<td>$D_{ref}$</td>
<td>Reference diameter</td>
</tr>
<tr>
<td>$A_L$</td>
<td>Liner area</td>
</tr>
<tr>
<td>$D_L$</td>
<td>Liner diameter</td>
</tr>
<tr>
<td>$A_{an}$</td>
<td>Annulus area</td>
</tr>
<tr>
<td>$L_{PZ}$</td>
<td>Primary zone length</td>
</tr>
<tr>
<td>$L_{SZ}$</td>
<td>Secondary zone length</td>
</tr>
<tr>
<td>$L_{DZ}$</td>
<td>Dilution zone length</td>
</tr>
<tr>
<td>$L_{RZ}$</td>
<td>Recirculation zone length</td>
</tr>
<tr>
<td>$\Delta P_{3-4}/q_{ref}$</td>
<td>Pressure-loss factor</td>
</tr>
<tr>
<td>$T_{max}$</td>
<td>Maximum combustor outlet temperature</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>$T_4$</td>
<td>Mean combustor outlet temperature</td>
</tr>
<tr>
<td>$\dot{m}_3$</td>
<td>Inlet air mass flow rate</td>
</tr>
<tr>
<td>$P_3$</td>
<td>Inlet pressure</td>
</tr>
<tr>
<td>$T_3$</td>
<td>Inlet air temperature</td>
</tr>
<tr>
<td>$D_3$</td>
<td>Diameter of compressor outlet area</td>
</tr>
<tr>
<td>$R_3$</td>
<td>Radius of compressor outlet area</td>
</tr>
<tr>
<td>$\dot{m}_f$</td>
<td>Inlet fuel mass flow rate</td>
</tr>
<tr>
<td>$T_f$</td>
<td>Inlet fuel temperature</td>
</tr>
<tr>
<td>$\dot{m}_S$</td>
<td>Air-flow rate through snout</td>
</tr>
<tr>
<td>$\dot{m}_{SW}$</td>
<td>Air-flow rate through swirler</td>
</tr>
<tr>
<td>$\dot{m}_{dome}$</td>
<td>Air-flow rate through dome</td>
</tr>
<tr>
<td>$\dot{m}_{an}$</td>
<td>Air-flow rate through annulus</td>
</tr>
<tr>
<td>$\dot{m}_h$</td>
<td>Air-flow rate through holes</td>
</tr>
<tr>
<td>$\dot{m}_{h,pz}$</td>
<td>Air-flow rate through primary holes</td>
</tr>
<tr>
<td>$\dot{m}_{h,sz}$</td>
<td>Air-flow rate through secondary holes</td>
</tr>
<tr>
<td>$\dot{m}_{cool}$</td>
<td>Air-flow rate through cooling slots</td>
</tr>
<tr>
<td>$\dot{m}_{h,dz}$</td>
<td>Air-flow rate through dilution holes</td>
</tr>
<tr>
<td>$A_o$</td>
<td>Snout outer area</td>
</tr>
<tr>
<td>$D_o$</td>
<td>Snout outer diameter</td>
</tr>
<tr>
<td>$R_o$</td>
<td>Snout outer radius</td>
</tr>
<tr>
<td>$\psi$</td>
<td>Divergence angle of the diffuser</td>
</tr>
<tr>
<td>$L_{dif}$</td>
<td>Diffuser length</td>
</tr>
<tr>
<td>$A_S$</td>
<td>Snout area</td>
</tr>
<tr>
<td>$D_S$</td>
<td>Snout diameter</td>
</tr>
<tr>
<td>$D_{O,SW}$</td>
<td>Swirler outer diameter</td>
</tr>
<tr>
<td>$D_{I,SW}$</td>
<td>Swirler inner diameter</td>
</tr>
<tr>
<td>$\beta_{SW}$</td>
<td>Vane angle of blades</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Inclination angle of the dome</td>
</tr>
<tr>
<td>$L_{dome}$</td>
<td>Dome length</td>
</tr>
<tr>
<td>$s$</td>
<td>Cooling slot height</td>
</tr>
<tr>
<td>$t$</td>
<td>Cooling slot lip thickness</td>
</tr>
<tr>
<td>$t_w$</td>
<td>Flame tube wall thickness</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Bleed ratio</td>
</tr>
<tr>
<td>$C_{d,h}$</td>
<td>Hole discharge coefficient</td>
</tr>
<tr>
<td>$A_h$</td>
<td>Total hole area</td>
</tr>
<tr>
<td>$D_h$</td>
<td>Hole diameter</td>
</tr>
<tr>
<td>$\Delta P_h/P_3$</td>
<td>Pressure-loss through a hole</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Orifice area ratio</td>
</tr>
<tr>
<td>$K$</td>
<td>Hole pressure loss factor</td>
</tr>
<tr>
<td>$\delta$</td>
<td>Momentum loss factor</td>
</tr>
<tr>
<td>$N_h$</td>
<td>Number of holes for each combustion zone</td>
</tr>
<tr>
<td>$D_{h,pz}$</td>
<td>Diameter of primary holes</td>
</tr>
<tr>
<td>$D_{h,sz}$</td>
<td>Diameter of secondary holes</td>
</tr>
<tr>
<td>$D_{h,dz}$</td>
<td>Diameter of dilution holes</td>
</tr>
<tr>
<td>$D_{h,dome}$</td>
<td>Diameter of dilution holes at dome</td>
</tr>
<tr>
<td>$AF_{st}$</td>
<td>Stoichiometric air-fuel ratio of fuel</td>
</tr>
<tr>
<td>$AF_{excess}$</td>
<td>Air-fuel ratio at primary zone (with approximately 10% excess air)</td>
</tr>
</tbody>
</table>