A simplified fuel evaporation mixing model for addition of singular components to multi-component fuels

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Abstract

This paper describes work undertaken in understanding the effect of differing fuel mixtures on micro gas turbine efficiency. For this case it was found that combusting jet fuel with additional volatile components ran with reduced thrust specific fuel consumption. To understand this behaviour a model was developed to calculate combustion efficiency with minimal computational effort using a blend of steady state fuel evaporation constants based on empirical data. It was found that the combustion efficiency in such an engine is largely controlled by evaporation rather than reaction kinetics or mixing. This fuel mixing model predicts the overall efficiency trends of the evaporation controlled combustion with a good level of accuracy.

Nomenclature

c_{pa}	Specific heat capacity of air at constant pressure
c_{pg}	Specific heat capacity of combustion gasses at constant pressure
D	Instantaneous droplet Sauter Mean Diameter
D_0	Initial Droplet Sauter Mean Diameter
F	Engine thrust
far	Fuel Air Ratio
	Mass Flow
P	Pressure
t	time
T01	Stagnation pressure at inlet
T012	Compressor temperature rise
T023	Combustor temperature rise
T_s	Droplet surface temperature
V	Volume
Y	Mass fraction
λ	Evaporation constant

Subscripts:

a	Air
Additive	Additive droplet properties
Blend	Blended droplet properties
Bulk	Bulk droplet properties
ce	Combustion evaporation process
cm	Combustion mixing process
e	Evaporation
f	fuel
L	Loss associated term
pz	Primary combustion zone
ref	Combustion reference dimension
s	Surface condition

Acronyms:

CEA	Chemical Equilibrium with Application
EGT	Exhaust Gas Temperature
MGT	Micro Gas Turbine
TSFC	Thrust Specific Fuel Consumption

Introduction

The purpose of this paper is to describe a simple model which can be used to determine the combustion efficiency of a micro gas turbine engine operating with a blend of bulk Jet A-1 and a single additional volatile component, butanol. The effect of blending butanol with the bulk fuel can be modelled quickly with a good degree of accuracy, explaining efficiency differences in engine operation depending on fuel content.

Specific Objectives

The paper intends to explain the effect of blending fuels of different volatility on MGT combustion efficiency, using fuel properties and a simplistic fuel mixing model with a fitting parameter to determine the effects of fuel blends on efficiency.

Modelling efficiency

The literature (Lefebvre 1989) indicates that gas turbine combustion efficiency is controlled by limiting rates, any one of which will reduce the overall combustion efficiency if its rate is not suffice to allow mixing to take place within the combustor. These limiting rates include the rate of fuel evaporation, mixing rate and reaction rate, as shown in equation 1.

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$$\eta_c = f(airflow\ rate)^{-1}\left(\frac{1}{evaporation\ rate} + \frac{1}{mixing\ rate} + \frac{1}{reaction\ rate}\right) \quad [1]$$

The literature indicates that overall combustion efficiency is largely controlled by the evaporation and reaction rates, where as mixing rate only plays a part at very high efficiencies (near 100%). Hence, combustion effectively defined in equation 2 (Mellor 1990).

$$\eta_c = (\eta_{c\theta})(\eta_{ce}) \quad [2]$$

Calculations were performed to determine the reaction rate efficiency using empirical formulae (Lefebvre 1985) which indicated that the reaction rate was fast enough to complete the reaction within the combustor. The rate controlling step in this combustion process is therefore evaporation, which can be determined by equation 3 (Lefebvre 1985) .

$$\eta_{ce} = 1 - e^{\left(\frac{[-36\times10^6 P_{in}]V_{pz}\lambda}{[T_{pz}D_0^2 f_{pz} m_a]}\right)} \quad [3]$$

Thus the overall combustion efficiency can be predicted using equation 3 assuming all other efficiencies assumed to be 100%. Combustion efficiency is now defined, in the case of this MGT as a factor of fuel properties, droplet size, mass flow, pressure and primary zone temperature, pressure, air fuel ratio and geometry.

Droplet Evaporation modelling

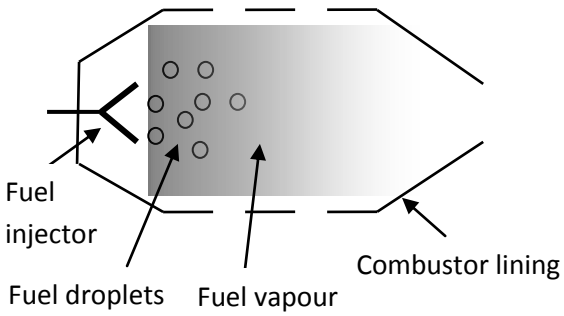

Figure 1: Fuel evaporation within the combustor

In the past droplet evaporation (figure 1) of multi-component fuels has been approximated as a steady state process. In recent years this method has been superseded as it is incapable of capturing the complex physical processes taking place inside of a multi-component fuel droplet. In this case the original droplet evaporation method has been altered to take into account two separate species, for the sake of simplicity. Calculation of differing species diffusion rates to the droplet surface were negated, along with the effect of other evaporating droplets in close proximity which add to the local fuel vapour pressure. Data calculated using this older method has been proven to predict overall combustor efficiencies effectively with minimal calculative effort correlating well with a large amount of empirical engine data (Lefebvre 1983)

Fuel droplet evaporation constant depends on a variety of factors including the temperature, pressure, thermal transport and mass transport properties of the fuel and surrounding gas along with the fuels volatility, geometry and size.

The steady state evaporation rate of a spherical droplet with given diameter can be defined mathematically (Lefebvre 1989) and is described in Equation 4.

$$\lambda = \frac{D_0^2 - D^2}{t_e} \quad [4]$$

Where λ is the steady state evaporation constant, D_0 is the initial Sauter Mean droplet Diameter *(SMD)*, t and D are the instantaneous time and droplet diameter respectively.

Droplet lifetime can be represented in terms of D_0 and λ (Lefebvre 1989) which can be shown using equation 5.

$$t_e = {D_o^2}/{\lambda} \quad [5]$$

Lefebvre's model makes use of an equilibrium condition between mass transfer number, B_M, and heat transfer number, B_T, which can be solved iteratively to predict the conditions at the droplet surface interface, where evaporation occurs. Such conditions include the surface temperature and evaporation constant of the fuel.

In order to calculate the droplet surface conditions vapour pressure at the surface, P_{Fs}, mass number of fuel and oxidizer, M_F and M_A, primary zone temperature T_{pz}, specific heat capacity of the air, $c_{Pa,}$ and vapour, c_{Pv} must be known. Such data sets were not determined for the fuel blend but for the individual fuels represented (bulk hydrocarbon Jet A-1 and butanol). Where necessary fuel data has been interpolated from technical literature in the case of butanol (BASF 2008), or calculated using empirical correlations and data in the case of Jet A-1 (Lefebvre 1989). Kerosene vapour pressure was determined using the Clausius-Clapeyron relationship as described in (Shepherd J.E. , Nuyt C.D. et al. 2000) and further sources were used for data not given elsewhere (Goodger 1980; BASF 2008; DBBST 2010)

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Analysis of past results

Past work has indicated that TSFC improvements are achievable through an increase in volatile fuel component when combusting jet fuel in MGT (Rye 2006; Rye 2007). In order to draw meaningful comparisons with theoretical data it is necessary to express the effectiveness of fuel burn in terms of combustion efficiency rather than TSFC, since most models in the literature use the earlier metric. It must be noted that data from previous work included thrust, temperature and fuel consumption information necessary to calculate this efficiency. Engine specific information has been sourced from the literature (Rye 2007) or assumed identical to similar sized MGTs where dimensions were absent in the literature (Kamps 2005; Ling, Wong et al. 2007)

Combustion efficiency can be calculated using engine performance and fuel data for a simple turbojet engine (Lefebvre 1999), using equation 6.

$$\eta_c = \frac{(heat\,released\,in\,combustion)}{(heat\,available\,in\,fuel)} = \left(\frac{\dot{m}_A c_p T_{023}}{q\dot{m}_A H}\right) \quad [6]$$

Where $\dot{m}_A$ is described as the compressor delivery mass flow, c_p is the specific heat capacity of the gas delivered and T_{023} is the temperature rise across the combustor. This is then divided by the heat available in the fuel for a given mass flow rate. The unknowns in this equation are the compressor delivery mass flow and combustion temperature rise, which can be found from the literature (Ling, Wong et al. 2007) and extracted from experimental results using Brayton cycle calculations.

Blend additive %	EGT (ºC)	Fuel Cons (g/sec)	Thrust (N)	Comb. Effic. (%)
Jet A-1	**617**	**4.63**	**91.77**	**79.6**
5% Butanol	**610**	**4.7**	**92.29**	**80.3**
10% Butanol	**620**	**3.9**	**93.87**	**96.0**
20% Butanol	**639**	**4.03**	**89.22**	**99.3**

Table 1: Previous Experimental Results

Experimental results in Table 1 were calculated assuming that the engine has compressor, turbine and nozzle efficiencies of 85%, 90% and 90% respectively, making use of experimental data.

It can be shown by rearranging Brayton cycle calculations that the temperature rise due to combustion, in the ideal case is given in the form of equation 7.

$$T_{023} = \left[EGT\left(\frac{\left(\frac{F}{\dot{m}}\right)^2}{2c_p}\right)\right] + \left[T_{012}\left(\frac{c_{pa}}{c_{pg}} - 1\right)\right] + T_{01} \quad [7]$$

Where *EGT* is the measured exhaust gas temperature, *F* is the measured thrust, $\dot{m}$ is the modelled mass flow of air using computational fluid dynamics (Ling, Wong et al. 2007) assuming maximum simulated mass flow as the engine is running at the 100% throttle setting. T_{012} is the total compressor isotropic temperature also calculated from the literature (Ling, Wong et al. 2007) and T_{01} is the ambient total temperature. Exhaust gas density was found by using Boyles' law having assumed that the exhaust gasses were ideal. The combustion temperatures, pressures and mass flows be further verified using other literature (Gonzalez C.A; Wong K. C.; Armfield S. 2008)

After the combustion temperature rise from the experimental data, T_{023} had been determined using Equation 2, the known fuel mixture was entered into NASAs CEA software (Chao 2008). In this way it was possible to model the maximum temperature rise produced in combustion and account for disassociation of CO_2 during this process. The calculated combustion temperature rise was then compared with the energy content of the fuel and fuel mass flow rate from experimental data in order to determine the overall combustion efficiency, as displayed in Table 1. This combustion efficiency was calculated using Equation 1.

Adapted Evaporation Model

Combustion efficiency was estimated using empirical calculations (eq. 3), however there were a number of unknowns in the equation for the MGT efficiency. Combustor inlet pressure was assumed to be identical to that of the same (KJ66) centrifugal impellor model which had been calculated in the literature using CFD (Ling, Wong et al. 2007). Other unknowns were calculated using CEA and the literature which was cited earlier for the cycle calculations. The remaining unknowns were reduced to the fuel evaporation rate and droplet size. The evaporation rate constant could be calculated using empirical calculations (Lefebvre 1989) although droplet size could not, thus D_0 was used as a fitting parameter. By altering D_0 whilst using kerosene fuel properties the combustion efficiency of the engine running on kerosene was matched. Once this droplet size was found it was used for the rest of the fuel mixtures, butanol replaced a fraction of the Jet A-1 whilst maintaining the initial D_0. This process was carried

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out to predict the steady state droplet evaporation constant across the range of the experimental data.

The model proposed in this paper suggests that the fuel can be treated as a two component mixture, one being the bulk fuel, in this case Jet A-1 and the other being the additive, butanol. Properties of each fuel are calculated separately and the evaporation rate of each fuel found at the estimated surface temperature according to the theory set out in the literature (Lefebvre 1989) which assumes that the fuel droplet is monodisperse, spherical and that all of the fuel species diffuse instantaneously within the droplet. This provides the droplet surface with a balance of fuels evaporating at the surface equal to the mass proportion of each fuel relative to the whole mass. Recently developed fuel evaporation models are capable of handling individual fuel components and numerically solving the droplet evaporation over time in a moving fluid flow. It was decided that in this case a complex numerical model was unnecessary as the overall efficiency can be modelled using the method set out in the literature (Lefebvre 1989).

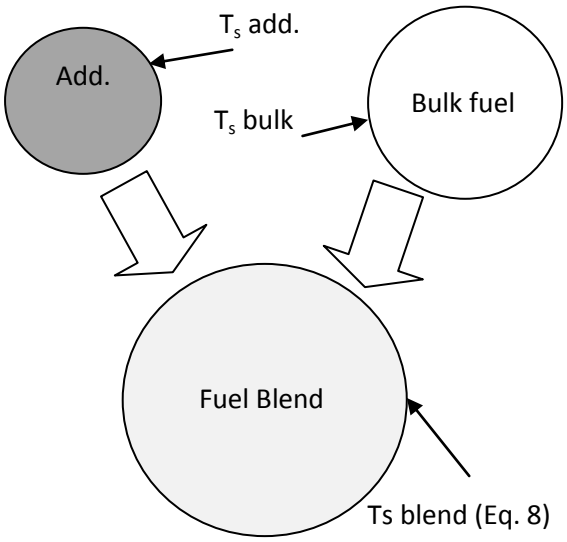

Figure 2: Fuel droplet model.

The author has developed a simple fuel mixing model in order to determine droplet evaporation. In this model the fuel droplet evaporation constants were calculated in the manner described by Lefebvre, assuming that there were two entirely different fuel droplets, one containing the bulk, multi-component fuel and the other containing only the additive (figure 2). Each droplet was treated separately until the iterative process had converged upon a solution, producing two separate surface temperatures. The surface temperature values were then averaged as a mass fraction weighted average to produce a new temperature which was used to calculate the evaporation constant for either fuel as described in equation 8.

$$T_{s.blend} = (YT_s)_{additive} + (YT_s)_{bulk} \quad [8]$$

Where Y_x denotes the mass fraction of x, bulk refers to the bulk hydrocarbon fuel and additive refers to the butanol content of the fuel.

Once calculated for the individual fuels, the evaporation constants were combined as a weighted average according to their overall molar mass in the fuel droplet as in equation 9.

$$\lambda_{blend} = (Y.\lambda)_{additive} + (Y.\lambda)_{bulk} \quad [9]$$

These evaporation constants have then be used to calculate combustion efficiency (using equation 3) in combination with CEA temperature estimates previously calculated, validating the models effectiveness.

Results and Discussion

Figure 3 illustrates that the fuel mixing model compares very well with experimental data, given that the experimental data contains ±5% variability in results. When a linear fit is carried out on experimental results there is a strong correlation (82% R^2) between the evaporation model and experimental results. This further implies that the MGT is operating within the evaporation controlled region and that the model can be accurately used to describe butanol and Jet A-1 combustion efficiencies as a function of the total butanol content of the fuel.

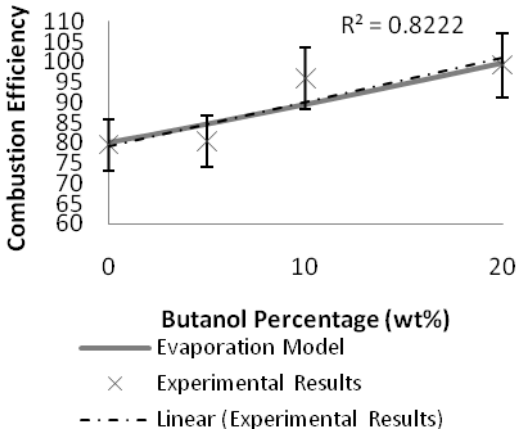

Figure 3: Comparison of modelling outcomes and experimental result.

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The discrepancy between the author's model and the empirical data could be due to a number of factors including the following:

- Unrealistic matching of the droplet size for each fuel blend. Each blend used the same droplet size, this will alter as a function of the fuel viscosity, injector flow number and geometry,

- Inaccurate prediction of the species diffusion within the fuel droplet in blended droplets. This must have little effect on the overall combustion efficiency as the model still predicts the efficiency trend well.

The author would like to stress that further numerical simulation and experimental work is necessary to fully validate this evaporation mixing model for use with other fuels within different gas turbines with different operating conditions.

This model may also be applicable to other small gas turbines, such as auxiliary power units or small electricity generating stationary gas turbines which have low pressure compressors and small combustion chambers.

Conclusions

- This work has shown a simple method of explaining the changes in efficiency within small evaporation controlled gas turbine combustors as a result of fuel blend.
- The described evaporation model has proven useful in understanding the underlying science behind this engines change in efficiency.

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