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Performance and environment as objectives in multi-criterion optimization of steam injected gas turbine cycles

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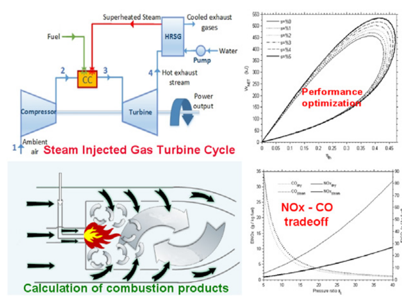
HIGHLIGHTS

- A thermodynamically precise performance estimation tool for GT cycles is presented.
- STIG application is provided to show its flexibility for any GT cycle and diluents.
- Constant TIT and net work output conditions have been compared and discussed.
- The model provides results to evaluate economic and environmental aspects together.
- It provides a precise estimation of adiabatic flame temerature and equilibrium species.

GRAPHICAL ABSTRACT



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ABSTRACT

Rapidly growing demand for gas turbines promotes research on their performance improvement and reducing their exhaust pollutants. Even small increments in net power or thermal efficiency and small changes in pollutant emissions have become significant concerns for both new designs and cycle modifications. To fulfill these requirements an accurate performance evaluation method which enables to see the effects on the exhaust gas composition is an important necessity. To fill this gap, a thermo-ecologic performance evaluation approach for gas turbine cycles with chemical equilibrium approximation which enables performance and environmental aspects to be considered simultaneously, is presented in this work. Steam injection is an effective modification to boost power and limit NO_x emissions for gas turbine systems. Steam injection also increases thermal efficiency so less fuel is burnt to maintain the same power output. Because of its performance related and environmental advantages, presented approach is applied on the steam injected gas turbine cycle and a precise multi-criterion optimization is carried out for varying steam injection, as well as equivalence and pressure ratios. Irreversibilities and pressure losses are also considered. Effects of each parameter on the net work and thermal efficiency as well as non-equilibrium NO_x and CO emissions are demonstrated. Precision improvement of the presented thermo-ecological model is shown and two main concerns; constant turbine inlet condition for higher net work output and constant net work output condition for lower fuel consumption are compared.

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1. Introduction

Gas turbine engines offer a wide range of power in relatively small sizes and are used in a variety of power generation purposes from utility power generation to transportation or military vehicles such as, airplanes, high-speed jets, helicopters, ships, tanks, locomotives and even in automobile and motorcycle turbochargers. As opposed to their competitor diesel engines, gas turbine engines can be operated on a wide range of fuels including natural gas which performs a cleaner combustion. The reason for this is that continuous-flow engines develop steady aerodynamics and flame kinetics which reduce the constraints placed on fuel properties for combustion such as limitations for RON (octane) number or cetane index. In addition, the fundamental characteristic of continuous combustion in a gas turbine engine is that the residence time at high flame temperatures (a key cause of NO_x formation) is capable of being controlled. A balance between smoke production and NO_x generation can also be easily secured [1–3]. According to some predictions gas turbines may furnish more than 80 percent of all new U.S. generation capacity in coming decades [4]. In addition to the advances in utility power generation, application of gas turbines in marine vessels have advanced significantly from only naval vessels in the 1970s to a broad range of commercial and new naval configurations [5]. Because gas turbines have wide operation flexibility and they meet an important portion of world's total energy demand their economic and ecological performance improvement have been significant concerns for the governments.

Although it is has long been realized that performance and emissions from gas turbines should be evaluated simultaneously, there are not more than a couple of analytical studies which investigate the performance of gas turbines together with their pollutant emissions. Some of them are given in Refs. [6–8]. Additionally, existing gas turbine models in the available literature treat the exhaust stream as air [9] or more precisely as a mixture of complete combustion products comprising of CO_2, H_2O, O_2 and N_2 only [8,10–18]. This simplifications will lack in precision although there is sufficient oxygen which can completely oxidize all the fuel because of the dissociations of combustion products at high temperatures. Some studies [19–24] use crude curve-fit equations or tables neglecting the type of fuel, equivalence ratio or effect of system pressure to calculate the properties of exhaust gas mixture. In some other studies exhaust gas properties are assumed to be constant regardless of changing temperatures and pressures [25–28]. Many studies also neglect the effect of pressure losses in gas turbine performance analysis [9,18,22,29]. Additionally, existing semi-analytical correlations [30–33] which are used by previous authors [8,23,28,34] to determine the levels of NO_x, CO and UHC need a very precise adiabatic flame temperature because all these pollutants are strongly dependent on adiabatic flame temperature especially NO_x. In these studies adiabatic flame temperature is calculated with the formula of Gülder [35] which is derived from curvefit data obtained from a chemical equilibrium code and which gives only approximate results in the case when steam is not present in the combustion chamber. This formula is not suitable for the case when steam is present in the combustion chamber i.e. to analyze steam injected gas turbines.

Heywood [36], Rashidi [37], Vissler and Kluiters [7] and Rakopoulos et al. [38], state that it is a good approximation for performance estimates in engines to regard the burned gases produced by the combustion of fuel and air as in chemical equilibrium and therefore knowledge of the exact gas composition inside the combustion chamber is critical for the accurate calculation of the thermodynamic cycle models of internal combustion engines. For this purpose a chemical equilibrium scheme is needed considering a certain number of species present inside the combustion chamber.

In this paper a more precise modeling approach is proposed which is based on calculating equilibrium exhaust species taking dissociations with temperature into account for estimation of thermodynamic properties of the working fluid and adiabatic flame temperature. In this paper adiabatic flame temperature is calculated using the exact equilibrium composition considering the effects of steam during combustion, so adiabatic flame temperature, accordingly the turbine inlet temperature and amounts of pollutants which strongly depend on adiabatic flame temperature are more precise than the previous works. Effect of this improvement to the adiabatic flame temperature and associated pollutant emissions can be seen in Table 2.

To obtain the equilibrium composition in steam injection case, the chemical equilibrium routines of Olikara and Borman [39] presented by Ferguson [40] were modified for H_2O injection and the equilibrium results obtained were compared with the results of computer programs GASEQ [41] and CHEMKIN [42]. The comparisons were quite satisfactory and presented at [43].

Proposed gas turbine model also takes pressure losses into account for better precision.

Many authors have investigated gas turbines and gas turbine cycles and have been working on their optimal emissions and performance [22–32]. Because steam injection makes considerable changes both on performance and NO_x emissions, steam/water injected internal combustion engines are of major concern for more than 30 years and scientist are still working on possible improvements of this well established development [8,11,18,44–51]. In steam injected gas turbines, maintaining a constant turbine inlet temperature increases the power output and thermal efficiency but increases the fuel consumption or the owner can elect to reduce fuel consumption and maintain the same nominal power output [4].

With the established model, thermodynamic properties of working fluid are calculated at all stations of a steam injected gas turbine cycle numbered in Fig. 1. Performance of the steam injected cycle is evaluated taking irreversibilities and pressure loses into account for varying steam injection, as well as equivalence and pressure ratios. Model results are compared with previous gas turbine models and improvements of the results are shown in Table 2. Effects of each parameter on the net work and thermal efficiency as well as non-equilibrium NO_x and CO emissions of the steam injected cycle are demonstrated. Two cases for steam injected gas turbines; constant turbine inlet temperature and constant net work output conditions which are preferred for increasing the net work output and lowering the fuel consumption respectively are examined and compared.

2. Modeling and simulation

A STIG cycle is depicted with its critical stations and dedicated station numbers in Fig. 1 and presented approach is used for the

Table 1
Gas turbine characteristic values for the simulation.

T_{amb} (°C)	15	η_{pump}	0.70
T_{fuel} (°C)	15	ΔP_{steam} (kPa)	405.3
T_{steam} (°C)	300	P_{in} (kPa)	101.325
TIT (°C)	1300	P_{exh} (kPa)	101.325
η_{cis}	0.87	P_{drop} (%)	0.04
η_{tis}	0.89	t_{res} (s)	0.002
η_{cc}	0.99	ϕ_{pri}	1.02