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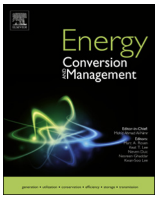

Effect of ideal gas model with temperature-independent heat capacities on thermodynamic and performance analysis of open-cycle gas turbines

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ABSTRACT

The ideal gas model with temperature-independent heat capacities is the most widely used thermodynamic model in gas turbine cycle simulations. This model is sometimes known as the “perfect gas model”. Closed analytical expressions for specific works and temperatures of the cycle are obtained in this way. If the results are accurate enough then the perfect gas model becomes a powerful analysis tool because its simplicity. For this reason it is the usually chosen option when energy, exergy or thermoeconomic assessments and optimizations of gas turbine cycles are carried out. However, there is a shortage of research works about the analysis of the uncertainty in the calculation of the performance parameters of open-cycle gas turbines with respect to the ideal gas model-based approach (ideal gas with temperature-dependent heat capacities). This analysis is presented in this paper for the simple cycle taking the net specific work output or specific power of the cycle and its Specific Fuel Consumption (SFC) as the performance parameters to be analyzed. First, to gain in internal coherence, an accurate thermodynamic model of the simple cycle based on the ideal gas assumption with temperature-dependent heat capacities is presented. For the sake of accuracy the isobaric heat capacity functions used in this model for every gaseous component present in the cycle are the employed in developing its actual multi-parameter equations of state as real fluids. Once this model is established the perfect gas simplification is applied which requires a procedure or rule to evaluate the constant heat capacity values needed. In many cases this rule is not always given or is not clearly specified in the specific literature. In this paper four different evaluation methods (named as A, B, C and D) are considered. These methods are designed to be directly run from known input fixed parameters of the cycle model. The analysis of the absolute and relative errors in computations with the perfect gas approach with the four heat capacity evaluation methods is then carried out. The main result from the analysis is that the own configuration of the open-cycle can lead to an increase (amplification) of the uncertainty in the values of the performance parameters. It is also observed that: (1) this amplification also depends on the method used to evaluate the heat capacities and (2) for a given evaluation method the amplification of the deviations may affect the performance parameters differently. As an example, maximum relative errors of 4.4% and −19.2% are observed in the net specific work output with methods C and D respectively for compressor pressure ratios from 5:1 to 40:1 and turbine inlet temperatures from 1200 K to 1800 K. For the SFC maximum values are −19.51% with method C and 3.95% with method D.

1. Introduction

Thermodynamic modeling of processes in thermal systems always requires the evaluation of the thermodynamic properties of the involved fluids at some point. As it is obvious and expected, the higher the accuracy of the thermodynamic models used for the calculation of the properties of the fluids, the higher the accuracy of the results and hence its validity. In the case of the processes where the fluid remains in the gas phase the ideal gas model is the most used in research works. This model is applied to study the open-cycle of shaft-power gas turbines very often but also for the investigation of new configurations of energy systems where these internal combustion engines may be present.

Examples of the latter are research works on gas turbine power plants, both in the case of simple-cycle based [1–7], regenerative cycles [5,8–10] or configurations with intercooling or reheating [6,11]; cogeneration plants [12]; combined heat and power (CHP) plants [13], some of them with integration of solid oxide fuel cells [14]; multigeneration systems [15–17], hybrid solar gas turbine plants [18] and combined cycle power plants [7,9,19–25].

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Nomenclature

E	relative error
M	molar mass
R	specific gas constant
T	temperature
$\bar{R}$	universal gas constant
$\bar{c}_p$	isobaric molar heat capacity
$\bar{f}$	molar fuel/air ratio
$\bar{h}$	molar enthalpy
$\bar{x}$	molar fraction
$\dot{W}$	mechanical power
$\dot{m}$	mass flow rate
c_p	isobaric specific heat capacity
f	fuel/air ratio
h	specific enthalpy
n	mole number
p	pressure
r	pressure ratio
w	specific work

Greek

Δ	absolute error
α	relative pressure loss
$\bar{\lambda}$	molar air/fuel ratio
η	efficiency

Subscripts

$C{-}T$	average compressor – turbine
a	air
c	compressor
cc	combustion chamber
cg	combustion gases
f	fuel
i	inlet
m	mechanical
net	net
o	outlet
os	isentropic outlet
t	turbine
th	theoretical, relative to the complete combustion reaction

Superscripts

a	air
e	stoichiometric
f	fuel
ig	ideal gas
pg	perfect gas

Abbreviations

CIT	Compressor Inlet Temperature
HR	Heat Rate
ISO	International Standard Organization
LHV	Lower Heating Value
RH	Relative Humidity
SFC	Specific Fuel Consumption
TIT	Turbine Inlet Temeperature
TOT	Turbine Outlet Temperature

Energy, exergy and thermoeconomic analysis and optimizations of the open-cycle gas turbines are often present in these works. In the majority of cases the ideal gas model is applied considering temperature independent heat capacities. This simplification of the ideal gas model is sometimes named as the "*perfect gas model*" and is the most widely used approach in research papers where the modeling of the open-cycle gas turbine is needed. This is the case of the set of aforementioned references. In general, this approximation is very powerful because it yields closed analytical expressions, for example, to compute work and heat transfers from energy balances or values of temperature in final equilibrium states of a system after a process. In addition, it is less time-consuming which could be especially interesting when optimization procedures are performed.

However, when the perfect gas model is applied the main issue is the choice of the constant values needed of the specific heats. This choice could commit the precision of the results depending on the nature of the processes and on the required accuracy in the calculations.

In the specific literature about open-cycle gas turbines there is a shortage of studies about the effect of the gas model in the thermodynamic modeling results of gas turbine power plants. From the knowledge of the author only two previous works exist [26,27] where this kind of evaluation is made. However, in [26] the analysis is carried out with a perfect gas model approach where the variation in the specific heats is introduced fixing different constant values depending on the point of the cycle. The results obtained in this way are compared with those obtained when the same value of the isobaric specific heat capacity (c_p) is used in the whole cycle and when two different values are considered: one for pure air and another for combustion gases. Therefore, the analysis of the deviations in [26] are not made respect to a "pure" ideal gas approach. On the contrary, the comparison among different models based on the ideal gas and real gas assumptions is performed in [27]. These authors also recognize the scarcity of this kind of investigations in the case of shaft-power gas turbines. The assessment is performed with three different set of models: (1) ideal gas based model, (2) models which accounts only the real gas effects and (3) models where the real gas and dissociation effects are taking into account. Therefore, the comparison between ideal and perfect gas-based approaches is not presented in [27]. A slightly different situation is found in the specific literature in the context of aero-gas turbines where few but some works have been published [28–30].

The main objective of this work is not to propose a method to choose the heat capacity values needed for the modeling of the open-cycle gas turbines with the perfect gas model. The aim of this work is to show that the own configuration of the open-cycle can result in a low accuracy in the predicted values when the perfect gas model is used for performance calculations. This effect can be found even when the perfect gas model exhibits good accuracy in computation of specific works in air compressor and turbine. In other words, the configuration of the cycle can give rise to the propagation (or not) of the intrinsic inaccuracy of the perfect gas model. In addition, the magnitude of the error propagation may depend on the chosen c_p – evaluation method. The latter is analyzed in the case of the simple cycle.

For the assessment of the results obtained with the perfect gas model a thermodynamic model for the simple cycle with the ideal gas model is firstly developed. For this purpose the most accurate c_p functions available in the literature are considered in this model to have accurate reference results. These functions are the used in the development of the multiparameter equations of state of the intake air, natural gas mixtures and combustion products constituents [31–35]. Secondly, the thermodynamic model of the simple cycle is built assuming temperature independent heat capacities for all the gases present in the cycle. Because in this case a c_p – evaluation method is