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Thermodynamic analysis of a gas turbine engine with a rotating detonation combustor

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HIGHLIGHTS

- Thermodynamic analysis of thermal power plants with pressure gain combustion.
- Time-resolved numerical model of rotating detonation combustor.
- Method of characteristic model of supersonic turbines.
- Guidance to select range of operation of gas turbines with pressure gain combustion.
- Gas turbine design trade-off between deflagration and detonation combustors.

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ABSTRACT

A rotating detonation combustor is a form of "pressure gain combustion" where one or more detonations continuously travel around an annular channel. Pressure gain combustion is a prospective technology being explored to advance gas turbine power plants. These thermodynamic cycles could potentially deliver a performance increase of 20% beyond the current state of the art. However, the combustor operates at extremely unsteady harsh conditions, and the integration of the combustor with the turbomachinery represent unprecedented aero-thermo-structural challenges. At a given instant each stream line experiences a different compression process through the combustor. In contrast to conventional combustors, where a steady approach is valid, in rotating detonation engines the flow particles entering the compressor will be exposed to different processes depending on the relative position of the rotor shaft to the detonation front. Hence, the overall performance assessment requires the development of ad-hoc tools suitable for this new class of combustors, and the modeling of the turbine exposed to supersonic pulsating flows. This paper presents a numerical tool to evaluate precisely the thermodynamic and non-isentropic processes across the entire engine. The NASA's Toolbox for the Modeling and Analysis of Thermodynamic Systems was used to implement new libraries to help us quantify the benefits of a rotating detonation engine versus the conventional technology equipped with constant pressure combustion. The new developed libraries, based on sets of physics-based principles, replicate the engine components performance. This model should allow the optimization of components with respect to energy availability to enable optimal engine sizing and operation. Finally, the paper presents the pressure ratios for which the rotating detonation based engine outperforms the conventional power plants based on the Brayton cycle.

1. Introduction

During the past seventy years' gas turbine engines have played a pivotal role advancing power generation and transportation technology. According to the International Air Transportation Association's annual report [1], only during 2015 a total of 3.5 billion passengers used air transportation systems. Despite, the clear benefit of aviation in the world economy, stringent environmental regulations require a decrease of emissions. Lee et al. [2] concluded, that air transport is responsible for a daily consumption of 5 millions of oil barrels per day, amounting to 781 million tons of CO_2 emission per year [1]. Globalization and competition,

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Nomenclature

A	flow area (m^2)
g	pitch between blades (m)
H	blade height (m)
M	Mach number (–)
P	pressure (Pa)
$P_{0,gain}$	pressure gain across the combustor (–) $P_{gain} = \frac{P_{0,out} - P_{0,in}}{P_{0,in}}$
R	combustor radius (m)
T	temperature (K)
V	velocity in the absolute frame of reference ($m\ s^{-1}$)
W	velocity in the relative frame of reference ($m\ s^{-1}$)
X_0	shock wave origin
m_0	mass flow at the engine inlet ($kg\ s^{-1}$)
m_9	mass flow at the engine outlet ($kg\ s^{-1}$)
m_f	mass flow of the fuel ($kg\ s^{-1}$)
V_9	nozzle outlet flow velocity ($m\ s^{-1}$)
V_0	flight speed ($m\ s^{-1}$)
Q_r	lower heating value (J/kg)
F	engine thrust (N)

Greek letters

α	flow angle in the absolute frame of reference (deg.)
β	flow angle in the relative frame of reference (deg.)
η	thermal efficiency (–)
π	compressor pressure ratio (–)
θ	momentum thickness at the trailing edge (m)
δ	displacement thickness at the trailing edge (m)
δ_{te}	ratio of tangential component of the trailing edge thickness

Subscripts

Out	outlet properties
Ref	refilling position
Wall	inlet wall
CJ	Chapman-Jouguet condition
Inj	injection conditions
In	inlet conditions
v	absolute conditions
W	relative conditions
min	minimum analyzed pressure ratio
ss	suction side
ps	pressure side
TRI60-5	low pressure ratio turbojet engine manufactured by Safran Power Units

Acronyms

PDE	Pulse Detonation Engine
RDE	Rotating Detonation Engine
RDC	Rotating Detonation Combustor
ZND	Zel'dovich-Neuman-Doring theory
SFC	Specific Fuel Consumption

demand a reduction in the transportation costs. Therefore, each year, engine and aircraft manufactures improve, on an average basis, the specific fuel consumption by 2.4%, which in turn has a direct impact on CO_2 emissions, but not the same linear response in terms of NO_X [3]. From the gas turbine engine perspective, the specific fuel consumption have been improved thanks to higher propulsive and thermal efficiency. The thermal performance enhancement of the Brayton - Joule cycle has been tuned with the rise on the Overall Pressure Ratio (OPR) and with higher Turbine Entry Temperature (T_4). However, Grote et al. [4] advised that the expected 5% aviation growth per year reported by Maisol and Harrison [5], will continue to surpass the reduction in emission rates. The intergovernmental panel on climate change [6], predicted that aviation will remain a major greenhouse emitter in the years to come. To answer this negative prospect, many disruptive ideas have focused on the development of advanced combined cycles [7] and on the re-design of the engine's core by adding intercooling and re-heating components [8,9]. However, the associated increase in complexity and weight remains prohibitive for propulsion applications. An alternative technology, explores the use of a new combustion process that can deliver a pressure gain [10–13] to the working fluid. The combination of heat addition and pressure rise, which contrast with the conventional Joule-Brayton cycle that operates at constant pressure, offers a great potential in terms of thermal efficiency. Although, there are different possibilities to achieve the pressure rise across the combustor, this paper addresses the rotating detonation combustor. In this case, the pressure gain is a direct consequence of the fast reaction mechanism of the detonation process, and does not require additional rotating components. Despite, great developments in the combustion technology [12], there has not yet been a complete engine analysis, that considers the effects induced by the high speed flows and the large pressure and temperature fluctuations generated in the combustor. The combustor-turbomachinery integration remains a scientific challenge that we carefully address in the present manuscript.

1.1. Thermodynamic cycle: Detonation vs Joule

Fig. 1a plots the temperature-entropy diagram of an ideal Brayton/Joule cycle and a steady detonation based cycle, under the same fuel input. Both principles have in common the isentropic compression process (2–3), while the combustion process (3–4) in the Joule cycle occurs at constant pressure, by contrast pressure rises through the detonation, and the combustor outlet temperature (4′) is higher. Therefore, the detonation cycle offers a higher potential for the expansion phase (4–5′) which could result into a more efficient system in terms of specific fuel consumption and thrust to weight ratio [14]. Fig. 1b reveals a thermal gain, of the detonation cycle, of more than 20% at low compression ratios (P_3/P_2), however, this improvement decreases monotonically with the pressure ratio.

1.2. Rotating detonation combustor and gas turbine engines

Voitsekhovskii [15] proposed in the 1960s the use of controlled waves traveling circumferentially around an annular channel. The detonation wave was sustained, within the initial part of the combustion chamber, thanks to a continuous axial injection of the fresh mixture. Such concept, allows the operation at kHz frequencies, which contrast with the few hundred Hz of the Pulse Detonation Combustor [16]. Additionally, it does not require complex valving nor a cyclic initiation of the detonation [17]. Fig. 2 represents the integration of a rotating detonation combustor with an axial compressor and an axial supersonic turbine stage. The flow field in the combustor is characterized by a detonation wave (A) moving in the counter clockwise direction (forward looking aft) and an oblique