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A Theoretical Review of Rotating Detonation Engines

*Ian J. Shaw, Jordan A.C. Kildare, Michael J. Evans,
Alfonso Chinnici, Ciaran A.M. Sparks, Shekh N.H. Rubaiyat,
Rey C. Chin and Paul R. Medwell*

Abstract

Rotating detonation engines are a novel device for generating thrust from combustion, in a highly efficient, yet mechanically simple form. This chapter presents a detailed literature review of rotating detonation engines. Particular focus is placed on the theoretical aspects and the fundamental operating principles of these engines. The review covers both experimental and computational studies, in order to identify gaps in current understanding. This will allow the identification of future work that is required to further develop rotating detonation engines.

Keywords: rotating detonation engine, detonative engines, propulsion, detonation shock waves, spin detonation engine

1. Introduction

1.1 Background

Detonative combustion is a potential propulsion method for aerospace systems, offering high efficiency and low mechanical complexity. In comparison, deflagration is generally considered easier to control and has therefore dominated both experimental and real world engine applications. Research into detonation engines has been limited due to the lack of the necessary tools required to design and analyse such systems [1, 2]. As such, practical development of detonation engines, notably the pulsed detonation engine (PDE) and the rotating or rotational detonation engine (RDE), has been limited [3]. Nevertheless, the application of detonation engines for propulsion is very promising, already proving to be compact, whilst providing highly efficient thrust generation [3–7]. This supersonic thrust could be utilised independently as a rocket engine, or as part of a gas turbine system. Interest in the development of RDE technology has grown and the challenges of utilising a more thermodynamically-efficient cycle have become better understood [8, 9].

Combustion can occur at both subsonic and supersonic velocities, known as deflagration and detonation, respectively. Deflagration is typified by a regular flame, which propagates at less than the speed of sound. The heat release may be used to expel the resulting products, generating thrust. Deflagration has been used in a broad range of applications to produce power. However, in theory, deflagration lacks the thermodynamic efficiency of a detonation system, which is a system

turbojets and ramjets. These low values for small-scale RDEs are likely due to the use of unoptimised designs, and low chamber pressures [31].

RDEs have been found to be successfully operable with a range of gaseous fuels including hydrogen, acetylene and butane, as well as various jet fuels [30, 31]. Air, pure oxygen, and oxygen-enriched air have all be used as oxidisers [31]. Each of these has a variety of advantages and disadvantages, in both performance characteristics, and ease of obtaining, transporting, and storing the oxidiser. Particular difficulty is noted in the transport of gases such as H_2 and O_2 due to the high risk regarding transportation and significant compression of these chemical species [59]. In the case of transporting liquid fuels such as LH_2 and LOx cryogenic units are also required, adding to the already challenging process. The performance characteristics for several of these fuel types will be discussed further in Section 4.4.

The detonation wave velocity in operational H_2 /air RDEs has been found to be on the order of 1000 m s^{-1} [30, 39]. In these RDEs, the operational frequencies are on the order of 4000 Hz, which produces quasi-continuous thrust [3, 32]. As wave speed is a key factor in the development of thrust, stable waves with high speeds are ideal for propulsion purposes. Stable detonation waves have reached maximum speeds in the range of $1500\text{--}2000 \text{ m s}^{-1}$ in most designs using a H_2 /air or H_2/O_2 fuel/oxidiser combination (more commonly the former), suggesting that there is open research into whether there is upper limit for detonation wave speed, and subsequently the thrust that may be produced [3, 22, 26, 60]. However, at very high frequencies (19–20 kHz), there may be multiple waves rotating around the annulus [60–62]. Multiple wave modes of propagation appear to be affected by fuel/oxidant equivalence ratio as well as total mass flow rate through the system. The high frequencies are a result of multiple waves travelling at approximately the same speed as the normal single wave. This phenomenon has the potential to provide more continuous thrust, though the higher frequency may limit I_{sp} due to insufficient refuelling of the detonation cell between waves. These wave modes have reliance on factors including fuel injection velocity, critical minimum fill height (discussed further in Section 4.3) as well as the detonation velocity [31]. Due to the inherent instabilities of rotating detonation waves, there are no specific relationships that can be determined between these factors and specific designs,