Combustion and Flame 158 (2011) 2023–2036

Contents lists available at ScienceDirect

Combustion and Flame

journal homepage: www.elsevier.com/locate/combustflame

The influence of heat transfer and friction on the impulse of a detonation tube

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ARTICLE INFO

Article history:
Received 11 August 2010
Received in revised form 28 December 2010
Accepted 22 February 2011
Available online 21 March 2011

Keywords:
Detonation
Pulse detonation engine
Detonation tube
Heat transfer
Friction

ABSTRACT

In the present study, we experimentally and numerically investigated the influence of heat transfer and friction on the performance of a single-shot detonation tube open at one end. Two kinds of specific impulse measurement were carried out with various tube lengths and levels of surface roughness, one by using a ballistic pendulum arrangement and the other by integrating the pressure history measured at the thrust wall. These measurements revealed the degree to which potential impulse can be exploited by the detonation tube after the impulse losses due to various wall loss mechanisms such as heat transfer and friction. The detonation tube obtained 89%, 70%, and 64% of the theoretical ideal impulse for electro-polished tubes at a ratio of tube length to diameter (L/D) of 49, 103, and 151, respectively. The impulse losses due to shear stress on the side wall of the detonation tube were found to have a dominant influence on the performance of the detonation tubes of $L/D = 103$ and 151, but the loss was remarkably small for $L/D = 49$ relative to that of the longer tubes. In addition to the experiments, a simplified one-dimensional gas-dynamic model was developed by considering heat transfer and friction as wall loss mechanisms and validated by the experimental results. This simplified model was found to predict the experimental results very well, especially in the range of L/D 103–151.

1. Introduction

A pulse detonation engine (PDE) obtains thrust by generating detonation waves intermittently [1,2]. PDEs have recently been recognized as a potential aerospace propulsion system [3,4] and were demonstrated as a rocket system by Kasahara et al. [5]. The basic structure of a PDE is a straight circular tube with one end closed and the other end open. Figure 1 shows a schematic diagram of the general PDE cycle. The tube is initially filled with a combustible mixture of reactants (Fig. 1a) and ignited at the closed end (Fig. 1b). A detonation wave is initiated there and propagates through the reactants, leaving a mixture of high-pressure combustion products behind the wave (Fig. 1c). The detonation wave exits as a strong blast wave into the surrounding air, and then the high-pressure products in the tube expand and are exhausted from the tube, allowing the pressure in the tube to decay to the ambient level (Fig. 1d). A PDE obtains thrust in the opposite direction from that of the blowdown of the exhaust gas at this stage. Finally, to return to the initial condition of the cycle, the combustion products are purged from the tube by replacing them with inert gases (Fig. 1e).

The PDE system has potential advantages compared to conventional aero-propulsion systems in reduced mechanical complexity, high thermodynamic efficiency, and high specific impulse (I_{sp}). Since unburned gas is compressed by a shock wave before combustion, the PDE is able to produce high-enthalpy gas without a complex compression mechanism, which is necessary for conventional propulsion systems. In addition, since the isovolumetric combustion takes place due to the detonation wave propagating at hypersonic speed, the performance of the PDE should be higher than that of systems using the Humphrey cycle (isovolumetric combustion cycle) and Brayton cycle (isobaric combustion cycle) in the case of an air breathing PDE [6] and pulse detonation turbine engine. Moreover, it is easy to increase the performance by using simple mechanisms, such as an extension tube for partial filling (Sato et al. [7], Endo et al. [8], and Kasahara et al. [9,10]) and a nozzle (Morris [11]).

For simplicity, in the primary stage of studies on PDEs, a detonation tube (DT) that produces a single detonation wave is typically used to estimate the performance of PDEs, and its single-shot specific impulse, I_{sp}, is often used as a performance metric. Endo et al. [12,13] analytically and Wintenberger et al. [14] quasi-analytically/quasi-empirically predicted the flow field inside the tube and calculated the performance of the DT under the assumption that the flow inside the tube is isentropic. However, a number of different experiments have shown that the measurement values of I_{sp} of the DT are lower than the analytical values (Takeuchi et al.

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doi:10.1016/j.combustflame.2011.02.017

Nomenclature

A	a/a_{CJ}, non-dimensional sound velocity
a	sound velocity
c_p	specific heat at constant pressure
C_f	friction coefficient
C_h	heat transfer coefficient
D	tube diameter
D_{CJ}	detonation velocity
f	shear stress per unit mass
g	gravitational acceleration
I	impulse
$I_{end\text{-}wall}$	impulse obtained as the integral of the pressure history at the thrust wall
$I_{pressure\text{-}deficit}$	impulse loss emerging as the pressure deficit due to heat transfer and friction
I_{isen}	ideal impulse obtained using isentropic flow assumption
$I_{net\text{-}thrust}$	impulse obtained in the method of a ballistic pendulum
$I_{shear\text{-}stress}$	impulse loss due to shear stress
I_{sp}	specific impulse
L	tube length
l_w	effective wire length
M	number of discrete segments for the initial Taylor expansion wave
m_{prop}	propellant mass
m_t	tube mass
m_w	wire mass
N	number of discrete segments on the C_+ characteristic corresponding to the detonation wave
Pr	Prandtl number
p	pressure
p_{pl}	plateau pressure
q	heat loss per unit mass
R	ideal-gas constant
R_a	arithmetical mean roughness
r	distance from the supporting point of the wire
S	$s/\Gamma R$, non-dimensional entropy
s	entropy
T	temperature
T^0	stagnation temperature
T_w	wall temperature
t	time from detonation initiation at the closed end of the tube
t_{cyc}	time when the pressure at the closed end of the tube decays to the ambient level
t_t	time when the rear boundary of the Taylor wave arrives at the open end of the tube
t^*	time when the exhausting rarefaction wave arrives at the closed end of the tube
t_{ws}	time when the pressure at the open end of the tube decays to the ambient level
U	u/a_{CJ}, non-dimensional particle velocity
u	particle velocity
v_0	initial velocity of the detonation tube
x	distance from the closed end of the tube
x_{imp}	initial displacement of the impactor
x_m	horizontal maximum displacement of the ballistic pendulum
Γ	isentropic index for the Chapman-Jouguet state
γ	specific heat ratio for unburned gas
$\eta_{end\text{-}wall}$	$I_{sp,end\text{-}wall}/I_{sp,isen}$, specific impulse efficiency
$\eta_{net\text{-}thrust}$	$I_{sp,net}/I_{sp,isen}$, specific impulse efficiency
ρ	gas density
ρ_w	linear density of wires
τ	ta_{CJ}/L, non-dimensional time
τ_w	shear stress per unit surface
ξ	x/L, non-dimensional distance
Ψ	non-dimensional shear stress per unit mass

[15], Laviolette et al. [16], Kasahara et al. [17]). We believe there are two reasons for this. The first reason is the influence of the initiation process of the detonation wave. In the analytical models proposed by Endo et al. and Wintenberger et al., the detonation wave is assumed to be directly initiated at the closed end of the tube, which is different from the actual flow in which the detonation wave is initiated through a so-called deflagration-to-detonation transition (DDT). In the case when the detonation wave occurs just inside the exit of the tube through the DDT, acoustic waves caused by the expansion of the detonation products reach the exit of the DT prior to the detonation wave, resulting in spillage of the propellant and hence an impulse deficit (Takeuchi et al. [15], Harris et al. [18], Kiyanda et al. [19]). The second reason is the influence of wall loss mechanisms such as heat transfer and friction, and this influence is the primary theme of the present study and has been the theme of several previous studies. Sichel and David [20] applied the analysis of the shock tube boundary layer proposed by Mirels [21] and Hartunian et al. [22] to the boundary layer behind a detonation wave moving past a flat plate and predicted the heat flux there with the assumption that the flow field behind the detonation wave is steady and constant. Using a modified Reynolds analogy in their model, Sichel and David related the heat flux to the shear stress. Skinner [23] analyzed the flow field in the tube one-dimensionally by the method of characteristics and by applying a Reynolds analogy to the non-steady Taylor expansion to investigate the influence of the heat flux and shear stress. Edwards et al. [24] experimentally observed the pressure and velocity deficits behind the detonation wave caused by the effect of heat losses. Edwards' pressure, velocity, and heat flux measurements confirmed the analysis models of Sichel and David [20] and Skinner [23].

In recent years, in response to the expectations regarding the practical application of PDEs, many experimental and numerical studies evaluating the thrust of PDEs have been performed. Laviolette et al. [16] experimentally found that the specific impulse generated in the DT remarkably decreases as the tube aspect ratio of length to diameter, L/D, increases. They explained these results with the simple analytical model of a flow field and showed that the heat losses and frictional losses have a dominant influence on the performance of the DT. Kasahara et al. [17] and Kojima [25] confirmed that the specific impulse losses due to heat transfer increase exponentially with increasing L/D by conducting experiments in very long tubes. Radulescu and Hanson [26] calculated the flow field of the DT with the non-steady physical model proposed by Skinner [23] and predicted how the specific impulse changes with increasing L/D. In their study, they considered only heat transfer as wall losses. Their model is in good agreement with the pressure and specific impulse measurements conducted in a number of different experiments. Owens and Hanson [27] developed the one-dimensional model initially proposed by Owens et al. [28] and Mattison et al. [29] by considering heat conduction in addition to heat convection and friction. They confirmed the validity of their model by comparing the heat flux and shear stress predicted by their model with those predicted by the Navier–Stokes model. Moreover, they showed with experiments and a one-dimensional model that in addition to heat transfer and