A computer-based tool for preliminary design and performance assessment of Continuous Detonation Wave Engines

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Abstract
For preliminary design and performance assessment of Continuous Detonation Wave Engine (CDWE), a computer-based tool has been developed which considers an ideal and simplified model of a CDWE in combination with a diverging nozzle. The tool evaluates flow conditions at five points in the engine and provides an initial estimation of the engine performance, dimensions and mass. The tool has been used to study the hypothetical performance gain achievable from the integration of CDWE in the lower and/or upper stages of a launch vehicle such as the Ariane 5 ME. It is found that, under the considered assumptions, launcher performance could be increased significantly with the use of CDWE.

Abbreviations

A5ME	=	Ariane 5 Mid-life Evolution
CDWE	=	Continuous Detonation Wave Engine
CEA	=	Chemical Equilibrium with Applications
CJ	=	Chapman-Jouguet
GTO	=	Geostationary Transfer Orbit
LH2	=	Liquid Hydrogen
LOX	=	Liquid Oxygen
LRE	=	Liquid Rocket Engine
LRP	=	Liquid Rocket Propulsion Analysis program
MS	=	Margin of Safety
PDE	=	Pulsed Detonation Engine
SART	=	Systemanalyse Raumtransport (Space Launcher System Analysis)
STSM	=	Space Transportation System Mass
TDW	=	Transverse Detonation Wave
TOSCA TS	=	Trajectory Optimization and Simulation of Conventional and Advanced space Transportation Systems
ZND	=	Zel'dovich, Von Neumann, and Doring

Nomenclature

A	=	Cross-sectional area [m^2]
A_p	=	Pre-exponential or frequency factor [-]
D	=	Detonation velocity [m/s]
E	=	Young's modulus [Pa]
E_a	=	Effective initiation energy [J/mol]
F	=	Thrust [N]
H	=	Enthalpy [kJ/kg]
I_{sp}	=	Specific impulse [s]
K	=	Geometric parameter, l/h [-]
L	=	Length [m]
M	=	Mach number [-]
P_{loss}	=	Injector pressure loss [%]
R	=	Universal gas constant [J/(mol K)]
S	=	Safety factor [-]
T	=	Temperature [K]
V	=	Volume [m^3]
a	=	Detonation cell size [m]
b	=	Longitudinal cell size [m]
d	=	Diameter [m]
f	=	Detonation frequency [1/s]
g	=	Gravitational acceleration [m/s^2]
h	=	Fresh mixture layer height [m]
l	=	Distance between two successive TDWs [m]
m	=	Mass [kg]
n	=	Number of TDWs [-]
p	=	Pressure [Pa]
q	=	Absolute velocity [m/s]
r	=	Radius [m]
t	=	Wall thickness [m]
u	=	Axial velocity [m/s]
$\dot{m}$	=	Mass flow rate [kg/s]

Greek letters			**Subscripts**		
Δ	=	Distance between annular walls [m]	0	=	Total
α	=	Ratio of mean pressure forces, p_x/p_y [-]	1	=	Inlet
β	=	Dimensionless density, ρ_3/ρ_2 [-]	2	=	Detonation
γ	=	Specific heat ratio [-]	3	=	Combustor exit
ε	=	Expansion ratio [-]	4	=	Hypothetical throat
η	=	TDW aspect ratio [-]	5	=	Nozzle exit
θ	=	Flow inclination angle [deg]	c	=	Chamber
κ	=	Mass fraction from previous TDW [-]	e	=	Exit
λ	=	Length of the TDW reaction zone [m]	i	=	Inner
ρ	=	Density [kg/m^3]	m	=	Fresh mixture
σ	=	Yield stress [Pa]	n	=	Nozzle
υ	=	Poisson's ratio [-]	o	=	Outer

1. Introduction

The use of Continuous Detonation Wave Engines (CDWE) for space applications has gained a large interest in the recent past. In theory, the detonation regime of combustion offers a promising alternative for traditional fuel burning methods based on deflagrations due to the higher efficiency of the thermodynamic cycle and the more stable burning in smaller chambers [1]. Therefore, detonation engines are expected to deliver a higher performance with respect to conventional Liquid Rocket Engines (LRE). Compared to Pulsed Detonation Engines (PDE), CDWE can provide a nearly steady thrust level in a more compact design (higher thrust-to-weight ratio) and is more suitable for operation in low pressure environments. Moreover, it generates a reduced vibration environment and requires only one detonation initiation. To study the potential performance gain achievable with CDWE, a simple computer-based tool has been developed which allows fast preliminary design and performance assessment of the engine. The tool comprises an engineering model of the engine and provides besides the engine performance also an estimation of the dimensions and mass of the engine. The tool has been used for preliminary investigation of CDWE integration into an existing launch vehicle and the corresponding hypothetical performance gain. In this paper, the underlying principles and working methods of the model are presented, as well as the preliminary results of the design studies.

2. CDWE model

Preliminary design and system analysis tools are typically required to be simple and fast to make them suitable for parametric studies with rapidly changing configurations while providing reasonably accurate results. A detailed simulation of CDWE would be complex and time consuming. Therefore, a simplified engineering model of an ideal CDWE has been developed and validated with published data from previous numerical and experimental studies.

The CDWE under consideration consists of an annular cylindrical combustion chamber combined with a diverging nozzle. As shown in Figure 1, the chamber is closed on the side where the fuel is injected (1), and open on the other side where the nozzle is attached to (3). Detonation takes place close to the injector head (2), after which the burned products expand through the combustion chamber and thereby reach supersonic velocity before exiting the chamber. They can then be further expanded through a diverging or aero-spike nozzle to increase the performance. In the present model, flow conditions are evaluated at five main cross-sections in the engine; 1) the combustor inlet, 2) the detonation wave front, 3) the combustor exit, 4) the theoretical throat section where the flow would be sonic, and 5) the nozzle exit. The model also provides an initial estimation of the engine performance, dimensions and mass.

To enable all the functions of the tool, the following input parameters are required:

- Injection conditions: temperature, pressure, propellant mass flow rate and mixture ratio, fresh mixture Mach number and assumed pressure loss through the injector
- Gas generator mixture ratio and mass flow rate
- Nozzle expansion ratio, fractional length, and wall thickness
- Remaining engine component masses (turbo-pumps, gas generator, valves)
- Safety, correction and efficiency factors for material properties, mass estimations, nozzle, etc.
- Design mode: CDWE design for a given thrust level or a given combustion chamber geometry

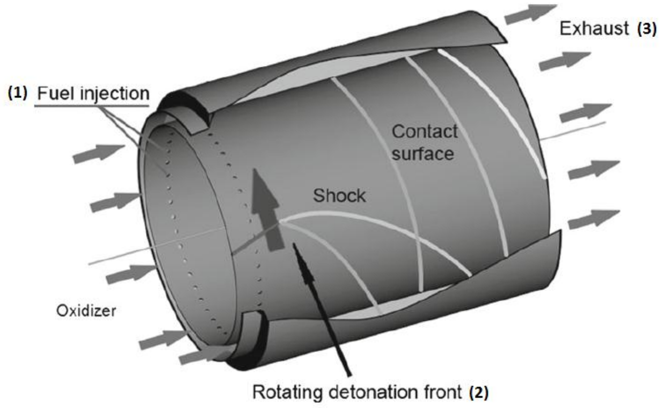

Figure 1: Simplified schematic of a CDWE combustion chamber [2]

2.1 Assumptions

The ideal CDWE model is based on the following simplifying assumptions:

- Steady-state engine operation
- Negligible heat losses and friction at the walls
- Uniform flow in the cross section where flow conditions are evaluated
- Ideal, one-dimensional Chapman-Jouguet (CJ) detonation
- Complete mixing and burning of the cryogenic propellants (LOX/LH2)
- No interaction between the burned detonation products and the fresh mixture
- Ideal gas and frozen composition at all points behind the TDW in the chamber

Additional assumptions that are relevant for a specific part of the model are stated where applicable.

2.2 Combustion chamber

The principle of CDWE is based on the formation of continuously propagating detonation in an annular combustion chamber. The fresh mixture is continuously injected into the chamber and burned by one or more Transverse Detonation Waves (TDWs). The burned products then expand isentropically towards the exit of the combustion chamber, reaching maximum acceleration and supersonic velocity before exiting the chamber [1, 3]. This eliminates the need for a geometrical throat, such that a diverging nozzle can be attached directly to the chamber exit. The structure of the TDW and the flow inside the combustion chamber is shown in Figure 2.

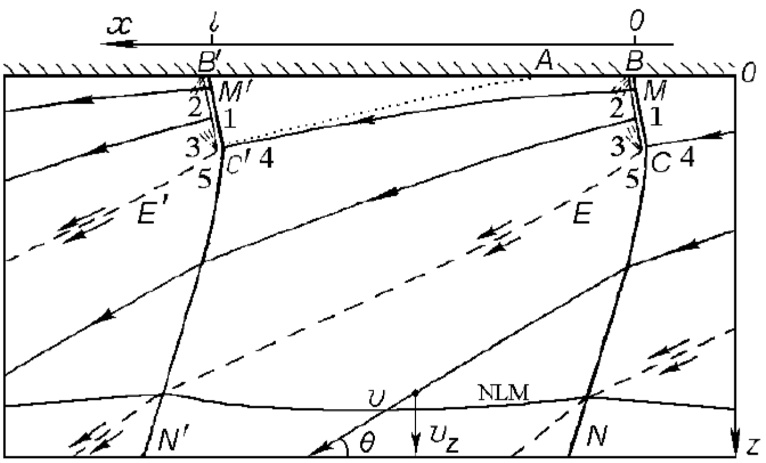

Figure 2: TDW and flow structure inside the combustion chamber [1]

The z-coordinate is in axial direction, and the x-coordinate is measured along the circumference of the chamber. The line BC represents the TDW. The length of the period of the flow field in x-direction is $l = (\pi d_c)/n$ where d_c is the chamber diameter, and n the number of TDWs. The necessary condition for obtaining an effective detonation regime is the continuous renewal of the fresh mixture layer ahead of the TDW. The height of this layer h should not be lower than the critical value for detonation h^*, which is related to the characteristic length of the TDW reaction zone λ according to $h \approx h^* \approx (17 \pm 7)\lambda$ [1]. When the fresh mixture is assumed to be premixed, the value of λ depends only on the time of the chemical reaction, and can be approximated by the detonation cell size a with the relation $\lambda = 0.7a$ [1]. The value of a can be determined using the method of Vasiliev and Nikolaev (1978) [4] based on the physiochemical data of the mixture. The formula for the longitudinal cell size b is obtained by assuming that the induction time obeys an Arrhenius relationship with temperature:

$$b = \frac{1.6D}{x} \frac{E_a}{RT} \frac{A_p \cdot \exp(E_a/RT)}{[O_2]} \quad \textbf{(1)}$$

It allows the calculation of the cell size for any mixture if the kinetic parameters A_p and E_a of the mixture are known. They are obtained from experimental data such as Lundstrom & Oppenheim (1969) [5] for H2-O2 mixtures. Then, the lateral cell size $a \approx 0.6b$ [4] and the critical fresh mixture layer height for detonation is $h^* = (12 \pm 5)a$ [1].

The CJ detonation parameters are calculated with the NASA computer program CEA (Chemical Equilibrium with Applications) [6]. The CJ model is based on the conservation laws for continuity, momentum, and energy together with basic thermodynamics that also apply for shock. It assumes that the flow is one-dimensional and steady, and that the chemical reaction is instantaneous, such that the reaction zone is infinitely thin. The model's representation of detonation is known as ideal detonation and may be used to estimate the detonation velocity and pressure [7]. The offset of ideal CJ values with experimentally measured values is typically equal to $D/D_{CJ} = 0.8$ for the detonation velocity [8] and $p/p_{CJ} = 0.55$ for the detonation pressure [9]. To incorporate this in the model, additional pressure losses may be considered, although it may be expected that the results from the model are to some extent optimistic.

The size of the combustion chamber is also related to the characteristic scale of the detonation wave front by means of the geometric parameter $K = l/h = (\pi d_c)/(nh)$. It is roughly constant for all annular cylindrical chambers, and has a value of 7 ± 2 in case of a gaseous oxidizer and a factor 1.5 - 2 larger in case of a liquid oxidizer. The minimum chamber diameter is then estimated from $(d_c)_{min} = hK/\pi \approx 80\lambda \approx 56a$ for chambers operating with a liquid oxidizer. The minimum and optimum length of the chamber are obtained from the empirical relations $L_{min} = 2h$ and $L_{opt} \geq 2L_{min}$. The minimum distance between the annular walls is given by $\Delta \geq 0.2h$, and the detonation frequency $f = D/l$ [1]. A schematic showing the chamber dimensions is given in Figure 3.

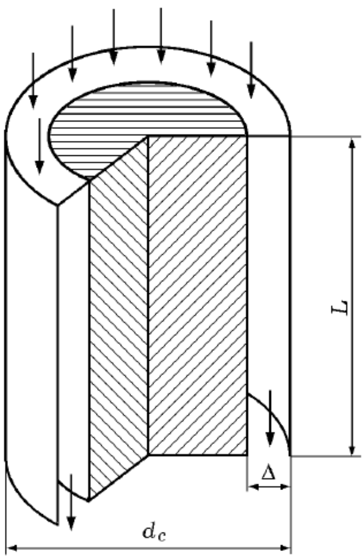

Figure 3: Layout of an annular cylindrical combustion chamber with diameter d_c, length L, and annular channel width Δ [8]

With the chamber geometry known, the isentropic expansion of the flow through the chamber can be determined. The density ratio $\beta = \rho_3/\rho_2$ can be solved iteratively from the equation [1]:

$$\alpha\left[\beta^{\gamma}+\gamma\eta^{2}/\beta-(\gamma+1)\eta\sin\theta_1\right]=(1-\eta\sin\theta_1)\left\{\gamma+1-\gamma\left[\left(\gamma+1-2\beta^{\gamma-1}\right)/(\gamma-1)-\eta^{2}/\beta^{2}\right]^{1/2}\Big/\cos\theta_1\right\} \quad \textbf{(2)}$$

Here, $\eta = h/l$ is the TDW aspect ratio and $\alpha = p_x/p_z$ is the ratio of the mean pressure forces acting between the fresh mixture flow entering the wave and the detonation products from the preceding TDW, in the x and z directions respectively. When the boundary flow line between these flows is assumed to be a straight line, $\alpha = 1$ [10], whereas the empirical value found by Falempin (2008) is equal to 0.75 [9]. Finally, θ_1 is the initial inclination angle of the wave to the z-axis and is empirically determined to be approximately 10° [10]. The stationary flow parameters at the combustor exit then follow from the following set of equations [1]:

$$\begin{aligned} p_3/p_2 &= \beta^{\gamma}, & q_3/q_2 &= \left[\left(\gamma+1-2\beta^{\gamma-1}\right)/(\gamma-1)\right]^{1/2} \\ \sin\theta_3 &= \eta\left(q_3/q_2\right)/\beta, & I_{sp} &= \left(p_3+\rho_3 q_3^{\,2}\sin^2\theta_3\right)/g \end{aligned} \quad \textbf{(3)}$$

2.3 Nozzle

Since the flow at the exit of the combustion chamber already reaches supersonic velocity due to the expansion in the chamber, there is no need for a geometrical throat. An annular nozzle compatible with the chamber configuration can therefore be attached directly to the chamber to continue the expansion of the flow, as illustrated in Figure 4. Aerospike nozzles are often proposed for CDWE integration, which can be particularly attractive for operation at sea level, but can only be considered for a limited range of expansion ratios. For a larger expansion ratio, a diverging nozzle such as a bell nozzle is typically more suitable. Although CDWE typically requires a larger expansion ratio than LRE for a given injection pressure due to the higher operating pressure of CDWE, the combustion chamber and the nozzle generally have smaller geometrical dimensions [9][11].

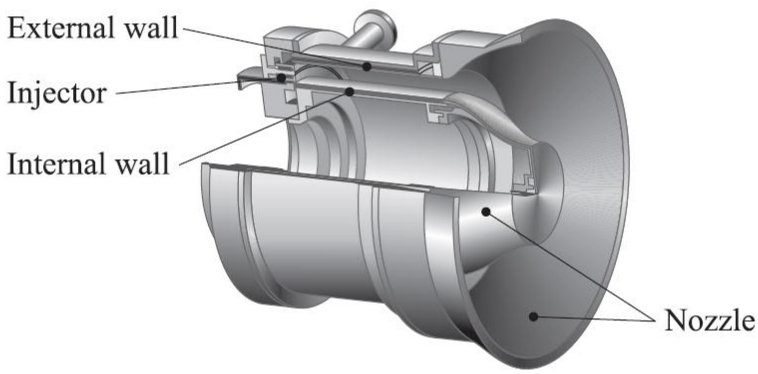

Figure 4: Layout of a CDWE showing the direct attachment of the nozzle [12]

The flow expansion through the nozzle is modelled using the ideal nozzle theory, which is based on the following assumptions [13]:

- The working fluid is homogeneous and obeys the perfect gas laws
- The flow is steady, one-dimensional, adiabatic, inviscid, and isentropic
- Friction, heat transfer, vibrations, boundary layer effects and transient effects are neglected
- The exhaust gases leaving the nozzle have an axially directed velocity
- The flow conditions are uniform over any cross-section normal to the nozzle axis
- There are no shock waves or discontinuities in the nozzle flow

Real performance for chemical rocket propulsion typically differ within 1-6% to the theoretical ideal values. The ideal parameters can be used for preliminary design of new rocket systems, which can then be improved by appropriate corrections. Wall friction losses are typically less than 2% of the total energy, and fluctuations in chamber pressure and mass flow rate are usually limited to 5% of the total values [13].

The acceleration of the flow through the nozzle is achieved by changing the nozzle cross-sectional area. According to the assumptions, this expansion process can be calculated using the conservation laws of continuity and energy in combination with the equation of state and the relation between the area ratio and the flow Mach number:

$$\begin{gathered}\dot{m} = \rho_1 u_1 A_1 = \rho_2 u_2 A_2 \\ H_0 = H_1 + 1/2\,u_1^2 = H_2 + 1/2\,u_2^2 \\ p = \rho R T \\ \frac{A}{A_t} = \left(\frac{\gamma+1}{2}\right)^{-\frac{\gamma+1}{2(\gamma-1)}} \frac{\left(1+\frac{\gamma-1}{2}M^2\right)^{\frac{\gamma+1}{2(\gamma-1)}}}{M}\end{gathered} \tag{4}$$

Since the ideal nozzle theory relates the flow conditions at the nozzle exit to the flow conditions at the throat for conventional rocket engines, it is necessary to calculate the hypothetical throat of a CDWE where the Mach number would be equal to 1 in order to apply the theory. This results in a hypothetical expansion ratio for the calculation of the expansion through the nozzle, which has an increased value compared to the actual expansion ratio of the nozzle.

In the thermochemical model, the chemical species are considered as thermally perfect gases with temperature-dependent thermodynamic properties. Any thermodynamic property of a mixture can be determined from the species properties for given pressure, temperature and species mass fractions using classical mixing laws. Standard state thermochemical data is thereby retrieved from the NIST-JANAF thermochemical tables [14]. The flow conditions at the nozzle exit are determined iteratively for increasing values of the temperature until convergence of the entropy is reached. Upon convergence of the entropy, the achieved performance is calculated with:

$$\begin{gathered}F = \dot{m}U_e + \left(p_e - p_a\right)A_e \\ I_{sp} = F/\left(\dot{m}g\right)\end{gathered} \tag{5}$$

The present model calculates the isentropic expansion process through the nozzle for a frozen composition of the mixture only. It is however known that frozen flow expansion typically underestimates the achieved performance. In reality, the expansion process in a nozzle lies in between the two limits of frozen and equilibrium flow. The real performance is therefore approximated by applying a correction factor which is derived from CEA simulations for existing liquid rocket engines.

2.4 Mass Estimation

In order to assess and compare the application of CDWE compared to conventional LRE, it is important to estimate the mass of the engine in addition to the performance. The total CDWE mass comprises the mass of the different components, including the combustion chamber, the injector head, the nozzle, the gas generator, the turbo-pumps, and the engine valves. The mass of the thrust chamber is estimated based on the geometry, internal pressure, and material properties. The masses of the remaining components are estimated with the internal DLR program LRP (Liquid Rocket Propulsion Analysis).

Regeneratively cooled combustion chamber

As can be seen in Figure 4, the annular combustion chamber comprises an internal and an external wall. As for conventional LRE, the high temperatures occurring inside the CDWE combustion chamber lead to rapid heating of the chamber walls. With temperatures largely exceeding the melting temperature of most materials, the need for active cooling is inevitable to maintain the temperature at a safe level. When cryogenic propellants are used, the walls can be cooled by circulating one or both of the propellants around the outer surface of the wall, known as regenerative cooling. For relatively small chambers, the double wall configuration is typically used, comprising an inner and outer shell separated by a small annular gap through which the coolant flows. Since the inner wall is not structurally connected to the outer wall, it is subject to the pressure exerted by the coolant and must therefore be thick enough to withstand considerable buckling loads. This leads to a typically heavy construction. More advanced channel-wall chambers, such as the Vinci engine chamber, make use of drilled passage ways in the chamber liner through which the coolant flows. A schematic of this type of configuration is shown in Figure 5. The advantage of such a configuration is that the inner and outer shells are connected, such that the outer wall becomes the principal load-bearing structure. This allows a minimal thickness of the chamber liner resulting in a reduced mass of the engine. Typical materials used are copper alloy for the chamber liner (i.e. Cu-7Ag-0.05Zr alloy for Vinci), and nickel for the outer cooling jacket. The high thermal conductivity of these materials combines well with the integral nature of the coolant passages and makes it possible to transmit heat at a very high rate [15, 16].

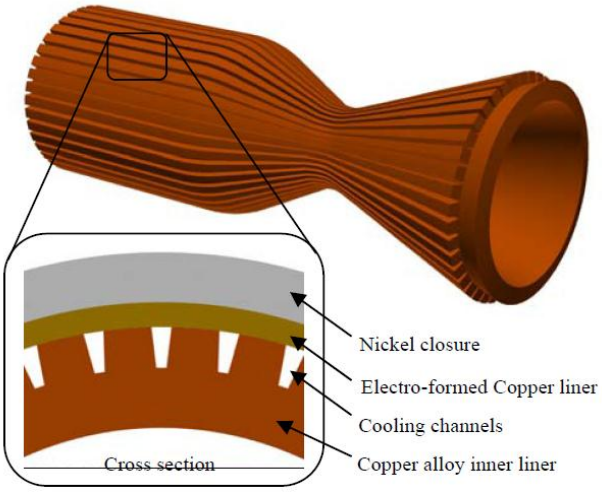

Figure 5: Schematic of cooling channels for a regeneratively cooled combustion chamber [16]

To estimate the minimum wall thickness required to withstand the internal pressure, the Barlow's formula for thin-walled pressure vessels is used, which relates the internal pressure in the vessel p_i to its outer diameter d_o and the material strength according to [17]:

$$t_{\min} = \frac{p_i d_o}{2\sigma + p_i} \tag{6}$$

where σ is the allowable yield stress of the material. A design safety factor of 1.5 is applied to the material strength to account for design contingencies and uncertainties such as material property variations, fabrication quality, load magnitude, etc. Also a minimum tolerance and a corrosion allowance are added to the calculated wall thickness [17].

Since the internal wall of a CDWE is subjected to an external pressure rather than an internal pressure. It is sized with the formula for the maximum buckling pressure [17]:

$$t_{\min} = \frac{d}{2}\left[p_o S \frac{4\left(1-\upsilon^2\right)}{E} \right]^{1/3} \tag{7}$$

where E is the Young's modulus, and υ the Poisson's ratio of the material. A safety factor S = 3 is applied to the buckling strength of the material. Fínally, the chamber mass is calculated by multiplying the volume of the malls with the material density according to $m = \rho V = \rho(\pi dtL)$. The design of the structure can be validated with the Margin of Safety (MS), which indicates the fraction by which the allowable load exceeds the design load. When positive safety margins are achieved under ultimate and yield load conditions, the design is accepted, otherwise redesign is necessary [15].

Diverging nozzle

In the present study, the CDWE is considered in configuration with a diverging bell nozzle. To specify bell nozzles an equivalent 15° half-angle conical nozzle having the same throat area and expansion ratio is commonly used. The conical nozzle with a 15° half-angle has become a standard because it provides a good compromise between weight, length and performance [18]. For a given expansion ratio ε and throat (or initial) diameter d_c of the nozzle, the conical nozzle exit diameter d_e and length L_n can easily be calculated from:

$$d_e = \sqrt{\varepsilon d_c^2}, \quad L_n = \frac{d_e - d_c}{2\tan 15°} \tag{8}$$

The length of the equivalent bell nozzle is then approximated by the so-called nozzle fractional length L_f, a design parameter for the ratio between the length of the bell nozzle and that of the equivalent conical nozzle, which is typically around 0.8 [18]. The volume of the nozzle shell then follows from:

$$V = \frac{1}{3}\pi L\left[\left(r_i + t\right)^2 + \left(r_e + t\right)^2 + \left(r_i + t\right)\left(r_e + t\right) - \left(r_i^2 + r_e^2 + r_i r_e\right)\right] \tag{9}$$

Multiplication with the material density gives the resulting nozzle mass. Rocket engine nozzles are commonly made of Carbon-Carbon (C-C) composites, which is the preferred material for single use, high-temperature (>1200-2000°C) space applications of short duration. The general properties of C-C composites are that they are light-weight and have the ability to operate at high temperature. They also have good mechanical properties such as fracture resistance, and low thermal expansion. Their long history of use in space programmes proves their advanced status in development and application [19].

3. CDWE Design Studies

To investigate the potential performance gain achievable with CDWE as compared with classic LRE, the integration of a CDWE in the Ariane 5 ME (Midlife Evolution) launch vehicle has been studied for both the lower and upper stages. The CDWEs are thereby considered to replace the current liquid rocket engines, Vulcain 2 and Vinci, respectively. They are designed to operate at a similar injection pressure, mixture ratio and mass flow rate as for the current engines, such that the current configuration of the tanks, turbo-pumps, and gas generator (in the case of Vulcain 2) can be reused without modifications. However, since the heat transfer for a CDWE is not estimated in the design tool, it cannot be guaranteed that the turbo-pumps of Vinci can be reused directly. The upper stage engine is therefore designed as a gas generator cycle instead of an expander cycle like Vinci.

With the estimated performances and masses of the CDWEs calculated with the design tool, optimization of the ascent trajectory and payload performance are done using two main internal DLR-SART tools:

- STSM (Space Transportation System Mass), a mass breakdown manager and mass estimation tool based on empirical correlations. The input comprises known subsystem masses and/or dimensions and the output is a complete mass breakdown of the launch vehicle.
- TOSCA TS (Trajectory Optimization and Simulation of Conventional and Advanced space Transportation Systems), which performs 2D and 3D ascent and descent trajectory simulations and optimization. It is used concurrently with the output from STSM and a chosen thrust-time history, for which the trajectory can be simulated and optimized iteratively to reach the desired target orbit with the maximum payload mass. The output provides all relevant trajectory data such as thrust, mass flow, acceleration, altitude, etc.

3.1 Ariane 5 ME

The Ariane 5 ME is a more powerful, cost-efficient, and versatile upgrade of the Ariane 5, aimed to fulfil the evolving demand for heavier payloads and re-ignition capabilities. The increased performance comes from the new cryogenic upper stage engine, Vinci, which is aimed to replace the current HM-7B cryogenic upper stage engine of the Ariane 5 ESC-A, and a bigger upper stage. Vinci is the first European re-ignitable cryogenic upper stage engine, characterized by the use of several advanced technologies such as an expander cycle and a deployable nozzle. It provides a vacuum thrust of 180 kN. The expander cycle eliminates the need for a gas generator to drive the LOX and LH2 turbo-pumps. LH2 is also used as a coolant flowing through rectangular coolant passages drilled into the copper alloy liner and closed by a nickel jacket. The extendable nozzle is made of lightweight ceramic material and allows the use of a large nozzle extension. The current Ariane 5 lower composite will be reused on the Ariane 5 ME without modification. It comprises two solid-propellant boosters and the cryogenic main stage equipped with the gas-generator cycle engine, Vulcain 2, which provides a maximum thrust in vacuum of 1359 kN [20-22]. The main engine characteristics of both Vinci and Vulcain 2 are summarized in Table 1.

Table 1: Vinci and Vulcain 2 engine main characteristics [20-22]

	Vinci	**Vulcain 2**
Injection pressure (H2/O2) [bar]	72/73	182.1/153.9
Mixture ratio	5.87	6.05
Total mass flow rate [kg/s]	39.5	320
Chamber pressure [bar]	61	117.3
Nozzle expansion ratio [-]	243	58.2
Nozzle length [m]	~3.3	~2.6
Nozzle exit diameter [m]	2.15	2.09
Exit pressure [bar]	0.012	0.1673
Vacuum thrust [kN]	180	1359 (988 SL)
Vacuum specific impulse [s]	464	433 (315 SL)
Total engine mass [kg]	589	2100

3.2 CDWE design for Ariane 5 ME

For both lower and upper stages, CDWEs have been designed to replace the current engines at constant injection conditions and for constant exit pressures. The engine design is strongly affected by additional assumptions, such as the assumed pressure losses in the injector (P_{loss}), and the Mach number of the fresh mixture (M_m). Bykovskii et al. (2008) [23] considered a pressure ratio of 8.5 in the injection system, which corresponded to the experimental data for a stoichiometric H2-O2 mixture. Davidenko et al. (2007) considered a similar value in their numerical H2-O2 CDWE simulations [24]. The static conditions of the fresh mixture flow before detonation are determined from the total injection conditions and the Mach number of the fresh mixture. In the studies by Davidenko et al. (2011) M_m is taken equal to 0.5, but found to increase across the fresh mixture layer from 0.5 in the middle to about 1 near the edge. Moreover, it was found that the pressure loss in the injection orifices increases when the Mach number increases [25]. In general, a larger pressure loss as well as a higher mixture Mach number will results in a lower static pressure of the flow in front of the TDW, and therefore also a lower detonation pressure and chamber pressure. However, lower chamber pressures typically also lead to smaller and thus lighter chambers, which can compensates the lower performance to some extent. Furthermore, an increase in the Mach number will also cause a decrease in the static temperature, which can result in significant detonation pressure rise, particularly at cryogenic temperatures.

For the present studies, CDWE design is done for both $M_m = 0.5$ and $M_m = 1$ at a pressure loss $P_{loss} = 85\%$. Additionally, a more optimistic scenario is considered assuming a smaller injector pressure loss of 50%, such that in total 4 different cases are considered for the 4 combinations of M_m and P_{loss}:

1) $P_{loss} = 50\%$ and $M_m = 0.5$
2) $P_{loss} = 50\%$ and $M_m = 1$
3) $P_{loss} = 85\%$ and $M_m = 0.5$
4) $P_{loss} = 85\%$ and $M_m = 1$

The results for the optimal case (1) and worst case (4) scenarios are given in Table 2.

Table 2: CDWE engine characteristic for Ariane 5 ME lower and upper stages

	CDWE_Upper_stage		**CDWE_Lower_stage**	
Scenario	**1**	**4**	**1**	**4**
Chamber total pressure [bar]	271	73	1188	301
Chamber outer diameter [mm]	143	123	178	101
Annular wall spacing [mm]	18	16	17	13
Minimum chamber length [mm]	135	224	112	121
Nozzle expansion ratio [-]	378	224	110.5	63.5
Nozzle length [m]	2.86	1.85	1.54	0.73
Nozzle exit diameter [m]	1.85	1.23	1.1	0.54
Vacuum thrust [kN]	190	182	1510	1428
Vacuum specific impulse [s]	498	475	461	436
Relative variation I_{sp} w.r.t. corresponding LRE [%]	**+7.3%**	**+2.4%**	**+6.5%**	**+0.7%**

It can be seen that even for the worst case scenario, a performance increase is achieved w.r.t. the reference engines. For the upper stage, an increase in specific impulse of approximately 34 s and 11 s is achieved for the best and worst case scenarios respectively, and for the lower stage 26 and 3 s. The thrust is only slightly increased for the upper stage, but more substantially for the lower stage, up to 5 and 11% respectively. Moreover, a reduction of the size of the chamber and the nozzle is achieved, in spite of the larger expansion ratios required. This is due to the smaller cross-sectional area of the combustion chamber. Finally, for similar injection pressures, the chamber pressures in the CDWEs are generally higher than those in the corresponding LREs.

3.3 Mass Breakdown

The engine mass estimation method explained previously was tested for the Vinci engine. An engine mass of 606 kg was estimated, which is within 3% of the real engine mass, and thus a reasonable approximation. For the masses of the engine components obtained with LRP, a margin of 20% is taken which was found to be the typical maximum offset with the real component masses from existing engines. For the mass calculation of the upper stage CDWE, a new power pack (gas generator and turbo-pumps) providing propellant at the same injection conditions as the Vinci engine was simulated with LRP. The estimated mass budgets of the CDWEs including margins are shown in Table 3.

The CDWE engine masses appear to be significantly reduced by roughly 15-30% in the optimal scenario and 45% in the worst case scenario. Despite the high chamber pressures, it is not surprising that the engine mass is reduced due to the significantly smaller size of the chamber in terms of diameter and length. The reduced engine masses may lead to substantial advantages in the payload performance of the launch vehicle. To assess this performance advantage, the current Vinci and Vulcain 2 engine masses are substituted with the CDWE engine masses while keeping the remaining mass budget of the launch vehicle constant. Then, the ascent trajectory and payload performance are optimized. The results are presented in the next section.

Table 3: CDWE mass breakdown for Ariane 5 ME lower and upper stages

	CDWE_Upper_stage		**CDWE_Lower_stage**	
Scenario	**1**	**4**	**1**	**4**
Turbo-pumps mass [kg]	130	130	640	640
Gas generator mass [kg]	10	10	20	20
Engine valves mass [kg]	40	40	300	300
Combustion chamber mass [kg]	30	20	130	30
Injector head mass [kg]	50	30	200	40
Nozzle mass [kg]	230	100	150	80
Total engine mass [kg]	490	330	1440	1150
Relative variation w.r.t. corresponding LRE [kg]	-99	-259	-660	-950
Relative variation w.r.t. corresponding LRE [%]	**-16.8%**	**-44.0%**	**-31.4%**	**-45.2%**

3.4 Trajectory and Payload Performance Optimization

The GTO target orbit for the Ariane 5 ME is defined by an apogee altitude of 35786 km, a perigee altitude of 180 km, and an inclination of 6°. For the launcher operating with CDWE, the ascent trajectory and payload performance are optimized for the same target orbit, considering an identical configuration of the vehicle in which only the engine masses and performances are substituted. Optimization is done for the launch vehicle operating with CDWE in the upper stage only (CDWE_Upper), in the lower stage only (CDWE_Lower), and finally in both upper and lower stages (CDWE_Both). Table 4 shows the results for the worst case scenario engines. Note that even if a reduction of the inter-stage length would be possible due to the smaller CDWE, this could lead to an additional mass reduction which has not been taken into account here.

Table 4: Optimized trajectory characteristics

	A5ME	**CDWE_Upper**	**CDWE_Lower**	**CDWE_Both**
Maximum acceleration [g]	4.035	4.029	4.026	4.020
Maximum dynamic pressure [kPa]	37.8	38.0	36.8	36.7
Total losses [m/s]	2025.11	1984.53	1952.87	1956.64
Payload mass [kg]	9696	10368	10264	11072
Relative variation [kg]	-	+672	+568	+1376
Relative variation [%]	**-**	**+6.93%**	**+5.86%**	**+14.19%**

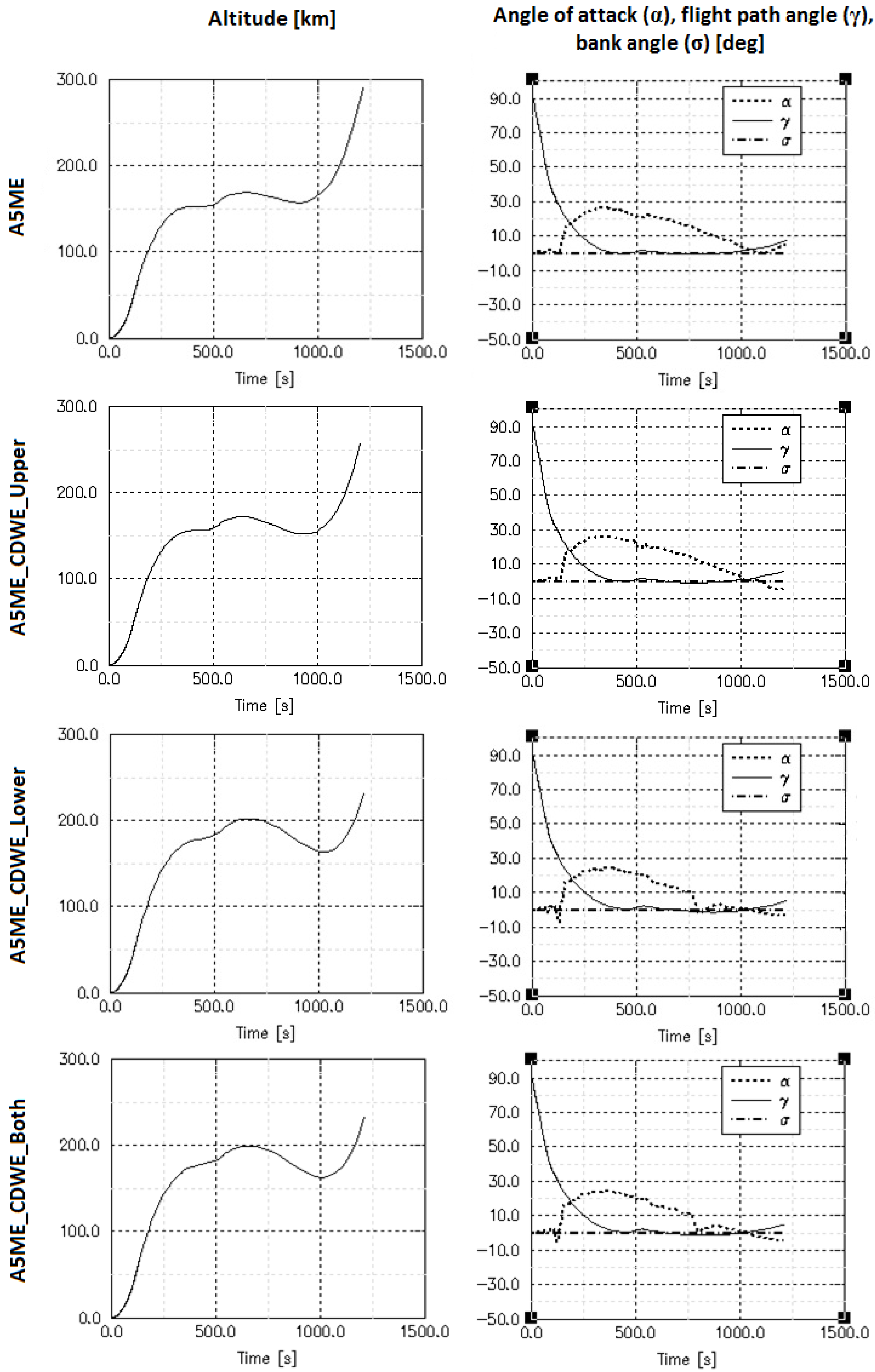

Figure 6: Altitude (left), and angle of attack, flight path angle, and bank angle (right) as a function of time for the optimized trajectories

It can be seen that the launcher performance can theoretically be increased with the use of CDWE. Considering CDWE in the lower stage gives only a slightly better performance than for CDWE in the upper stage (roughly 6 and 7% respectively). With CDWE in both the lower and upper stages simultaneously, the payload performance can be increased by approximately 14%, equivalent to nearly 1.4 tons. This is a significant improvement which clearly demonstrates the high potential of CDWE for space applications.

Some parameters characterizing the optimized trajectories are shown in Figure 6. From top to bottom, the trajectories are shown for the original A5ME, the A5ME with an upper stage CDWE, the A5ME with a lower stage CDWE, and the A5ME with both upper and lower stage CDWEs. The graphs show the altitude (left) and the and the angle of attack, flight path angle, and bank angle (right) of the trajectories as a function of time. Other characteristics, such as acceleration and Mach number, show a similar evolution as for the original trajectory.

4. Discussion and Conclusion

A preliminary design tool has been developed to enable fast parametric analysis and performance assessment of CDWE. The tool has been used to assess the integration of CDWE in the upper and/or lower stage of the Ariane 5 ME launch vehicle and the corresponding potential performance gain achieved. The results showed that an increased launcher performance can be achieved due to the higher specific impulse and reduced mass of the CDWE compared to LRE at the same injection conditions. With CDWE in both upper and lower stages, payload performance can be increased up to roughly 14%.

When considering the same injection conditions, the chamber pressures in CDWE are typically much higher than for classic LRE. This can be explained by the extreme pressure rise in the detonation process. The chamber pressure can be decreased by decreasing the injection pressure, meaning that the similar chamber pressures as for LRE can be obtained with CDWE at lower injection pressures. In launcher application this could lead to significant benefits at system level for the design of the complete injection system. Furthermore, CDWE has the possibility to obtain a similar performance as LRE at higher mixture ratios. In the case of a LOX-LH2 mixture, this allows the use of smaller tanks for the same propellant mass. However, such modifications would require a redesign of several components, which may not be justified if the performance gain is not substantial.

Although the studies have demonstrated the large potential of CDWE for space applications, it is nevertheless important to take into account that the obtained results are a product of many simplified and idealized assumptions.
For instance, the assumption of ideal Chapman-Jouguet detonation typically estimates detonation pressures about 80% higher than experimental values and the detonation velocity about 25% higher. The assumption that the detonation parameter $\alpha = 1$ typically results in a 1-2% higher performance than the experimental value $\alpha = 0.75$. Another important consideration, is the strong influence of the injection temperature on the detonation pressure in case of cryogenic propellants; a slight decrease of the injection temperature can cause a sharp rise in the detonation pressure. Finally, it should be noted that additional factors causing pressure losses in reality are not considered in the model, such as the expansion of propellant jets, non-uniform propellant mixing, mixture dilution with combustion products, deflagrative combustion of the fresh mixture with the burned mixture, shocks and shear layers in the flow expansion zones, and skin friction with the chamber walls. These phenomena can cause an additional decrease in the CDWE performance. It may therefore be expected that the results of the model are more optimistic than the reality.
For a more reliable analysis, the tool could be improved by replacing the current ideal CJ detonation approximation with a more accurate detonation model, such as the Zel'dovich, Von Neumann, and Doring (ZND) model. It would also be desirable to include a detailed chemistry model to enhance the calculation of several important parameters that strongly affect the CDWE design, such as dynamic detonation parameters like initiation energy, cell size, etc. This would also allow the tool to calculate the isentropic expansion for equilibrium flow without having to use CEA.

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