Aerospace Science and Technology 43 (2015) 350–359

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

Dimensioning of automated regenerative cooling: Setting of high-end experiment

L. Taddeo [a,*], N. Gascoin [a], I. Fedioun [b], K. Chetehouna [a], L. Lamoot [a], G. Fau [a]

[a] INSA Centre Val de Loire, PRISME, 88 boulevard Lahitolle, 18000 Bourges, France
[b] CNRS ICARE, Avenue de la recherche, 45100 Orléans, France

ARTICLE INFO

Article history:
Received 31 October 2014
Received in revised form 15 February 2015
Accepted 18 March 2015
Available online 24 March 2015

Keywords:
Regenerative cooling
Hydrocarbon fuel pyrolysis
Ramjet engine cooling efficiency
Energy saving strategies
Lab scale testing

ABSTRACT

Regenerative cooling is widely used in high-pressure and high-thrust fuel-cooled rocket engines, also suitable for hypersonic structures. The propellant duality in terms of functions (fuel and coolant) makes the thermal and combustion management quite challenging. Dynamics of the system must be studied to develop regulation and control strategies which should be performed with a response time lower than the lowest characteristic time found in supersonic combustion ramjets, i.e. about 1 ms. The present work aims at setting experiments at lab scale by simplifying the additional difficulty of supersonic flow, to determine appropriate regulation dynamics for latter model and control developments. A combustion chamber was dimensioned with similitude rules in terms of heat flux density, conversion rate, chemical compositions, dynamics. Computational Fluid Dynamics and analytical calculations were developed to dimension the experimental bench. It was found that a pyrolysis rate up to 100% can be obtained using ethylene as fuel at 50 bar and 1200 K and with a residence time of about 100 s. Combustion with air (adiabatic flame temperature up to 2400 K) will provide the required heat flux density. The operating range in terms of fuel pressure (10–50 bar), of fuel mass flow rates (50–100 $\text{mg}\,\text{s}^{-1}$) and of equivalence ratio (0.8 to 1.0) have been certified.

1. Introduction

Hypersonic flight (over Mach 5) is a very attractive technology, especially in terms of flight time reduction. Its most peculiar features, i.e. high velocity and long-distance utilization, fit to various technological applications, like air launched strike weapons, space transport vehicles, ground launched satellite [1–4].

Hydrogen and hydrocarbons propelled hypersonic flights are expected to be achieved in the coming years by Supersonic Combustion Ramjet (SCRamjet) engines [5]. This kind of air-breathing engines use the vehicle forward motion to compress incoming air, without any rotary compressor.

SCRamjet suffers from two main problems:

1. High temperature values in combustion chamber. Maximum total temperature can achieve values as high as 4500 K [5]. That determines a dramatic heat load toward the inner wall of the engine (up to 25 $\text{MW}\,\text{m}^{-2}$) [4,6,7], that even composite materials cannot withstand.
2. Low time allocated for combustion. Reactants (fuel-oxidizer) residence time in the combustion chamber is of about 1 ms [8]. Because of the high values of ignition delay times for liquid hydrocarbons, that raises difficulties for the combustion process to be regularly carried out [5,7]. This point is crucial. In fact, the development of an effective combustion process requires the presence in the injected propellant of species whose ignition delay times are low enough to ignite in few tenth of ms. Considering the temperatures achieved by the compressed air entering the combustion chamber, when a kerosene is used this goal is very hard to fulfill [9,10]. A solution would be to develop a longer combustor, but that would increase cooling channels pressure drop and determine a lower L/D efficiency [11].

Regenerative cooling is one of the most widely applied cooling techniques in liquid propellant rocket engines [12,13]. Many studies, particularly numerical, have already been performed on it. It has proven to be a suitable and effective solution for both problems 1) and 2) for hydrocarbon-fuelled vehicles [14,15]. Fuel acts as a coolant, flowing through cooling channels located between the inner and the outer wall of the engine, before being injected into the combustion chamber. A counter-flow heat exchange between a

---

[*] Corresponding author. Tel.: +33 758422823.
E-mail addresses: lucio.taddeo@insa-cvl.fr (L. Taddeo), nicolas.gascoin@insa-cvl.fr (N. Gascoin).

http://dx.doi.org/10.1016/j.ast.2015.03.015
1270-9638/

Nomenclature

c_p	heat capacity
D	diameter
ΔP	pressure drops
$\Delta H_{dec\ fuel}$	enthalpy of decomposition of fuel
$\Delta H_{comb\ fuel}$	enthalpy of combustion of fuel
$\mathrm{ER}_{\mathrm{e/a}}$	equivalence ratio of ethylene and air
E	energy
F	view factor
g	gravitational acceleration
H	height
h	convective heat transfer coefficient
K_{D}	Darcy's permeability
K_{F}	Forchheimer's permeability
k_{ther}	thermal conductivity
l	cooling channel length
L_{d}	porous disks thickness
$\dot{m}$	mass flow rate
Q	volumetric flow rate
S_{d}	porous disks cross section
S_{w}	combustion chamber wall surface
t	time
T	temperature

Greek symbols

ε_{e}	burned gases emissivity
Φ	heat flux density
μ	dynamic viscosity
ρ	density

Subscripts

burned gases	combustion products
combustor	combustion chamber
cool channel	cooling channel
exit	combustion chamber exit
external	cooling channel side
fuel	fuel (*n*-dodecane/ethylene)
in	cooling channel entrance
internal	combustion chamber side
out	cooling channel exit
oxid	oxidizer (air)
wall	combustion chamber wall

liquid or supercritical domain (fuel) and a gaseous domain (burned gases) is thus established. The possibility of exploiting regenerative cooling when non-hydrocarbon fuels are used has also undergone numerical investigations. Hydrocarbons are preferred for flight whose Mach number is under 8 [16].

When heated above 800 K, any hydrocarbon propellant undergoes pyrolysis. The endothermic behavior of the chemical reactions enhances its cooling capacity (corresponding to a chemical heat sink of about 1–1.5 $\mathrm{MJ\,kg^{-1}}$, being 3-4 $\mathrm{MJ\,kg^{-1}}$ the sensible heat sink [17]. The authors use the expression "chemical heat sink" to indicate the amount of heat absorbed by the fuel allowing the decomposition chemical reactions to occur, while they use the expression "sensible heat sink" to indicate the amount of heat absorbed by the fuel allowing its temperature to rise). The complex chemistry of light and heavy hydrocarbon fuels pyrolysis has already been object of studies [18], especially in the petro-chemical fields. Pyrolysis phenomena generate many species like hydrogen and light hydrocarbons (ethane, ethylene, acetylene, etc.) whose ignition delay times are very low when compared to the initial heavy fuel. That allows the combustion process to get completely realized in the combustion chamber, thus improving the rocket engine performance. A major challenge associated to the dual function of the fuel (coolant and fuel) is to provide a regulation strategy which could be compatible with the dynamics of the supersonic vehicles [5]. In fact, increasing fuel mass flow rate may not conduct to a thrust increase because in correspondence of fuel injection raise, heat load available to pyrolyse the fuel could remain constant. Only transient evolution of heat load through the structure could provide more energy to pyrolyse the increased incoming fuel mass flow. This is a strongly transient, coupled and multiphasic topic. This negative loop is illustrated in Fig. 1. It can also be noticed that controlling the thrust should be done with response times lower than 1 s (which corresponds to a traveled distance of 1 km at Mach 5).

The strong coupling between pyrolysis and combustion makes system control and thermal management a very harsh task. The impact of the most important operating parameter, i.e. fuel mass flow rate, on the engine thrust is still not clear. A further complications is the strong transient nature of these coupled phenomena in on-board application [5]. In addition, side effects like cooling channels blockage can be found, as fuel pyrolysis also originates coke deposits, which can stick to the wall of the channels [18–20]. That raises serious concerns because of two possible consequences:

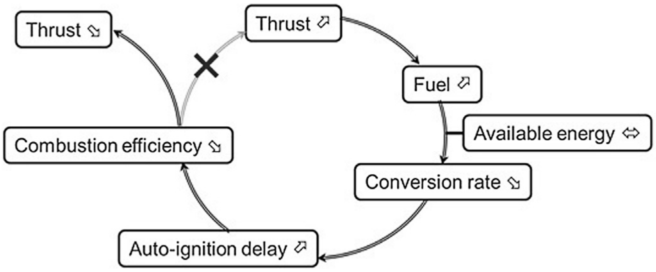

Fig. 1. Fuel mass flow rate increase: negative loop in terms of thrust variation.

1. A decrease in the cooling capacity of system.
2. The danger for the cooling channels to be jammed by coke.

In this sense many studies have been performed, like the COMPARER program developed by MBDA-France and by the University of Orleans [3,4], aimed at identifying, by both a numerical and an experimental analysis of the system, how the already mentioned operating parameter (fuel mass flow rate) interferes with pyrolysis-combustion coupling. A numerical code, the so-called RESPIRE code, able to simulate hypersonic vehicles regenerative cooling realized using a hydrocarbon liquid propellant, was developed and the dynamics of the coupled phenomena were determined. This program has highlighted the complexity of the matter, emphasizing the necessity of an empirical analysis of the system. The on-going activity is now focused on the implementation of a coupled experiment (fuel pyrolysis in cooling channels + fuel consumption in combustion chamber) to verify and validate the numerically acquired knowledge and particularly the dynamics of the phenomena. This step is necessary for a latter development of on-board regulation strategies (thermal management + thrust control).

The present work aims at setting up a remotely controlled experimental test bench suitable for the empirical analysis of pyrolysis-combustion coupling, by considering subsonic combus-