SPECIFIC PROBLEMS OF MICRO-TURBINE FOR MICRO-DRONES APPLICATION

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Abstract

The concept of micro-turbine seems to be a promising way, particularly for the application to micro-drones requiring a power of 10 W to 100 W. Validity of this concept to deliver the expected power is being studied in a research program at ONERA. This program comprises a global thermodynamic and thermal approach, numerical simulations and experimental work, with a particular attention on the combustion chamber.

Three specific problems connected to the reduced dimensions of the combustor can be addressed : low Reynolds number (thus laminar flow) yields poor mixing between fuel and air and between hot gases and fresh gases in the combustor, a small Damköhler number (residence time comparable to chemical reaction time) and the high level of external heat losses.

In order to evaluate the influence of these parameters on the combustion stability, two numerical approaches have been chosen : 0D computations like the perfectly stirred reactor and the partially stirred reactor, 3D simulations with ONERA's CFD code.

Concurrently, fuel/air mixing is studied experimentally without combustion in a micro scale premixed channel (visualization of a tracer using PLIF diagnostic). A set up for studying the combustion is under development.

Introduction

Micro-scale engines power generation and air vehicle propulsion applications have received considerable attention during the last decade [1 - 3]. These micro-scale engines are frequently based on MEMS technologies (Micro Electro Mechanical Systems) resulting from micro-electronics technologies (Si, SiC materials) which allow mass production. In terms of strength, at high temperature (1000 K), Si has comparable properties to common nickel alloys. The interest of miniaturized devices is essentially connected to their high potential specific energy (low weight and long duration) if compared to battery systems.

ONERA has compared different micro-engines concepts such as : piston engine, rotary engine (Wankel), gas turbine engine and systems based on thermoelectric effect, etc.

Among these micro-systems, the concept of micro-turbine, due to its compactness and its low weight, seems to be the most interesting, particularly for the application to micro-drones requiring a power of 10 W to 100 W.

However, the feasibility of this concept should be demonstrated. The general fluid dynamics problem should be carefully tackled : internal flows within small channels, combustion inside a micro-combustor, flow inside the micro compressor and the micro-turbine, as well as heat transfer to the walls.

The work presented in this paper is specially focused on the micro-scale combustor.

Micro gas turbine concept

This tiny engine, which uses the classical Brayton-Joule thermodynamics cycle, comprises successively the following parts : the centrifugal compressor, the combustion chamber and the inward-flow turbine connected to the compressor by a shaft (Fig.1).

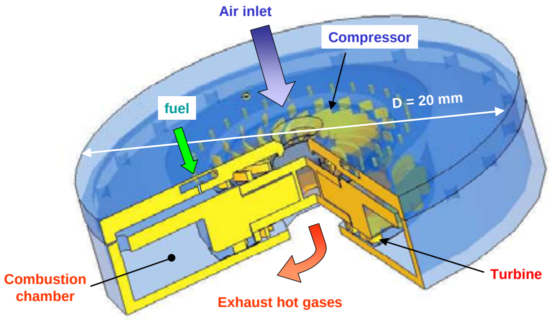

Fig. 1 : 3D representation of micro-turbine MITconcept

The fuel is injected right after the compressor, in the premixed channel. The rotor radial loads are supported on journal bearings on the periphery of the compressor.

The main features of the micro turbine are presented in table 1.

Table 1 : Main features of the micro turbine

Device volume	1.5 to 3 cm3
Mass flow	0.1 g/s to 0.5 g/s
Compressor pressure ratio	3 to 4
Temperature in the combustor	1 600 K to 1 800 K
Candidate fuels	H_2, C_3H_8, CH_4, C_2H_4
Fuel equivalence ratio	0.4 to 0.8*
Maximum wall temperature	1000 K (Silicon) to 1800 K (alumina)
Rotating speed	About 1 million rpm
Power density	3 000 MW/m3*

* depending on the fuel

The electric power will be obtained by a micro brushless electrical converter [4], that allows to reach a theoretical efficiency of about 90 % at high rotating speed (about 1 million rpm). With other micro-systems, it will be probably more difficult to obtain this level of net power with a good conversion and with the same compactness.

The ONERA research program comprises :

- a global thermodynamic and thermal approach,
- 3D flow computations inside the compressor, turbine and combustion chamber,
- experimental work in the combustion chamber,
- a study of gas bearings due to the high rotating speed and the gap (about ten microns) between the static and rotating parts,
- the choice of materials (Si, SiC, nickel alloys …) and the manufacturing of the micro-device,
- the development of igniter, specific sensors, etc.
- and, connected to these previous points, the architecture of the micro device.

Constraints for the combustion in a micro volume

There are three specific problems also connected to the small scale of the combustor [6 - 8] :

- a small Reynolds number (consequently laminar flows) which induces low mixing between fuel and air in the premixed channel (or mixing zone) and between hot gases and fresh gases in the combustor,
- a small Damköhler number (residence time divided by the characteristic chemical reaction time τc) is unfavorable to combustion stability,
- the external heat losses due to the high surface/volume ratio of the combustion chamber.

Computations

In order to evaluate the impact of previous parameters on combustion stability, two numerical approaches have been chosen :

- 0D with perfectly stirred reactor (PSR) and partially stirred reactor (PaSR),
- 3D with ONERA's CFD code.

With the 0D code [9], a preliminary estimation of combustion overall characteristics can be obtained. First of all, in order to understand the effect of small Damköhler number, the PSR model was used. This model allowed us to assess the range of stable combustion with a detailed finite rate chemistry [10]. The extinction limits has been determinated for different fuels (air-methane and air-hydrogen mixtures), inlet temperatures, equivalence ratio and heat losses. The gas temperature in the combustion chamber fueled by CH_4, versus mean residence time τ_r, with the PSR model, is presented for different levels of heat losses on Fig. 2. The inlet gas temperature is 800 K. Calculations start at an operating point with high combustion efficiency (long residence time). Then, residence time is slowly decreased until extinction occurs. We can see that extinction limits and gas temperature are strongly linked to the heat losses.

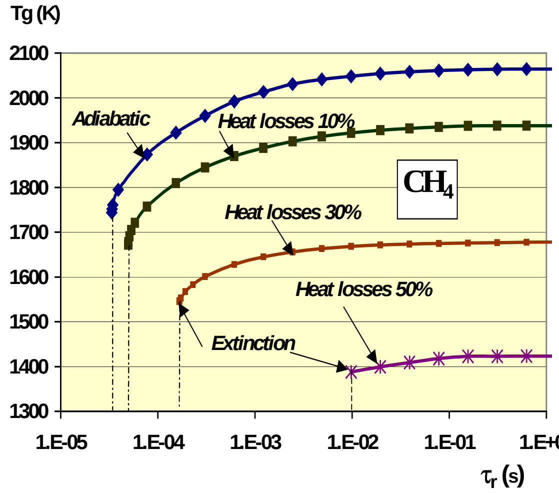

Fig. 2 : Gas temperature versus residence time for different levels of heat losses

The impact of non-perfect micro-mixing due to low Reynolds number was studied with PaSR models, derived from PSR. In the PaSR approach, three different micro-mixing models were investigated and compared : Vulis model [11], Interaction by Exchange with the Mean (IEM) model [12], and "assumed β-PDF" model [13]. The Vulis micro-mixing model was chosen to perform a parametric study. Mixing at molecular scale is defined by a characteristic micro-mixing time τ_m. This time has been evaluated to be between 10^{-5}s and 10^{-4}s for the micro combustor case.

With the PaSR model, a result of non-perfect micro-mixing due to low Reynolds number is presented in Fig. 3. In the same way as for the heat losses, the crucial influence of micro mixing efficiency on combustion is pointed out. It is shown that extinction limits are also strongly dependent on this parameter.

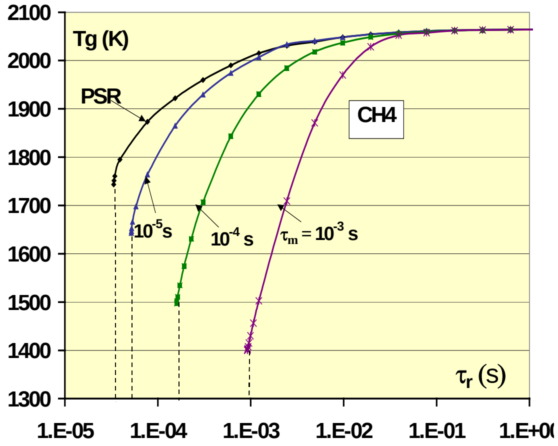

Fig. 3 : Gas temperature versus residence time for different mixing time scales (without heat loss)

From the estimation of heat losses and micro-mixing time scale for a realistic case (30 % heat losses and $\tau_m = 10^{-4}$s), the minimum residence time required for a stabilized combustion with CH4 is about 1 ms (Fig. 3).

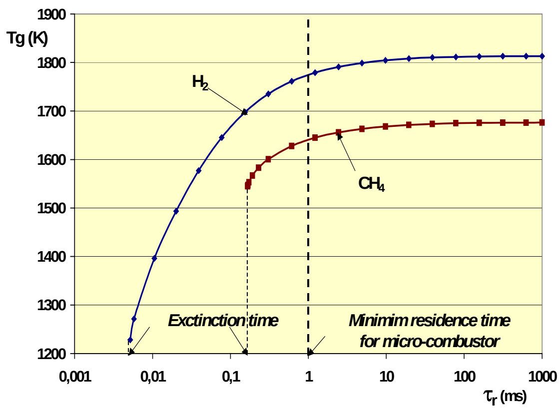

Fig. 4 : Gas temperature versus residence time for H_2 and CH_4

Therefore, for a Damköhler number of 1, we can calculate the minimum volume of the combustion chamber using the formula $V_{min} = m' . \tau_{r,min} .r . T_g / P_g$ (m' is the mass flow, r is the gas constant, T_g and P_g are the mean temperature and the pressure in the combustion chamber).

For micro-turbine conditions we must respect a minimum volume of about 600 mm^3. For hydrogen, this volume can be divided by 10, but gas temperature and chemical efficiency decrease strongly.

With the 3D CFD code called CEDRE, developed at ONERA, we simulated the real geometry of the MIT combustor.

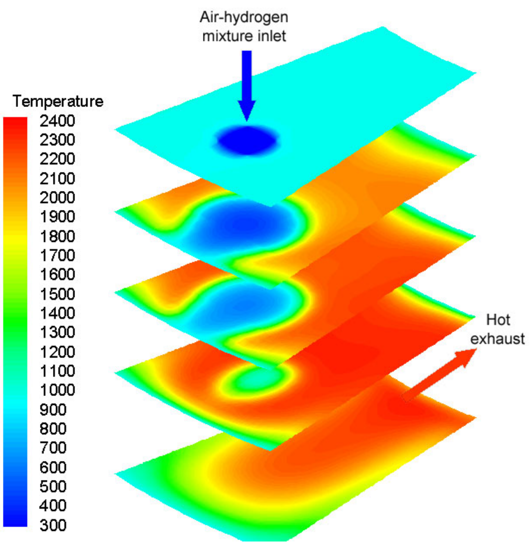

Fig. 5a : Gas temperature inside a sector of the micro-combustor – ONERA CFD code

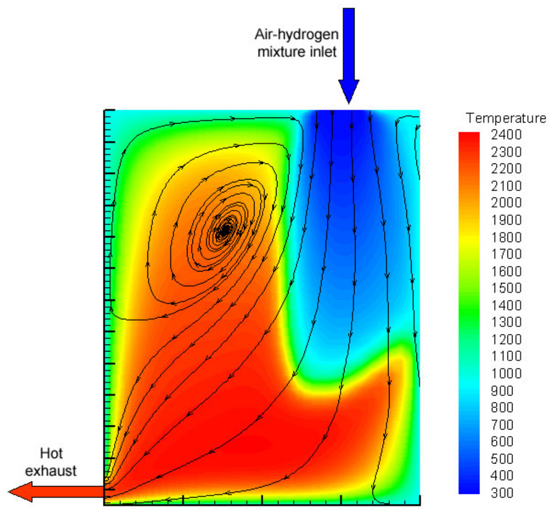

Fig. 5b : Streamlines and gas temperature in a cross-section of the combustor

The operating conditions are : air/hydrogen premixed flow; gas inlet temperature : 300 K ; equivalence ration : 0.6 ; wall temperature : 950 K; Ecklund model with 7 reactions. This allowed to determine the influence of geometric parameters on combustion stability. Indeed, as a consequence of the 0D model, micro-mixing must be improved and the combustor geometry must sustain well organized and strong recirculation zones. Therefore, an optimized residence time distribution can maintain a sufficient mixing between fresh and hot gases (Fig. 5a and 5b – MIT configuration).

Experimental study of mixing

At the same time of the numerical computations, an experimental study was carried out. The fuel/air mixing was investigated without combustion (Fig. 6) in the premixed channel by means of the visualization of a tracer using PLIF diagnostic [14] (Fig. 7).

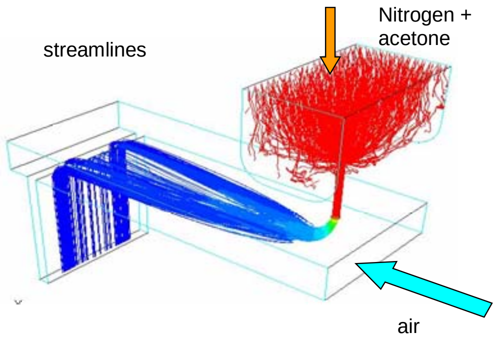

Fig. 6 : Premixed channel (FLUENT simulation)

Raw fluorescence images were corrected for background luminosity, non-uniformities in the collection optics and variations in the laser sheet profile before conversion into fuel concentration. Fluorescence intensity, right at the injector exit where fuel concentration was perfectly known, is used for auto-calibration.

Typical PLIF results are presented in Fig.8a, 8b and 8c.

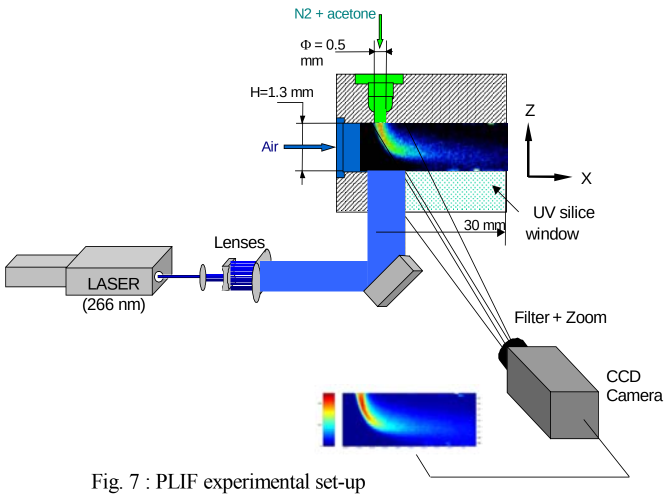

Fig. 7 : PLIF experimental set-up

Fig. 8a shows a comparison for three Reynolds numbers 100, 250 and 500. The first one is a laminar case without fluctuation. When flow velocity increases, turbulent structures appears which improves mixing between air and fuel.

Fig. 8b shows results with turbulence promoters for the previous three Reynolds numbers. An additional turbulence is created which increases the global mixing. Other types of turbulence promoter geometries are under investigation.

Fig. 8c, the influence of the ratio between fuel and air mass flows on the mixing is shown.

This kind of results will contribute to improve the mixing, in the premixed channel, by choosing the geometry according to the air and fuel mass flows.

In fact, the Reynolds number of the air flow should be as high as possible. The design of turbulence promoters should be very effective to produce 3D structures. The ratio between the mass flux (ρu) of fuel and air plays also a significant rôle on the micro-mixing. These are preliminary results that will be further examined and will be completed by other experiments.

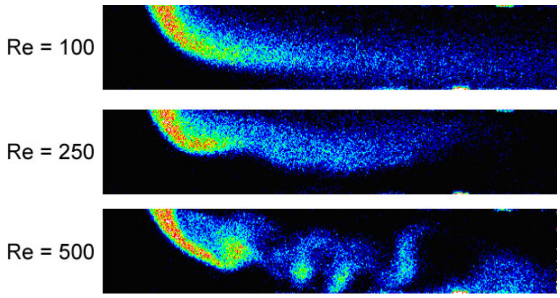

Fig. 8a : Images for three Reynolds numbers

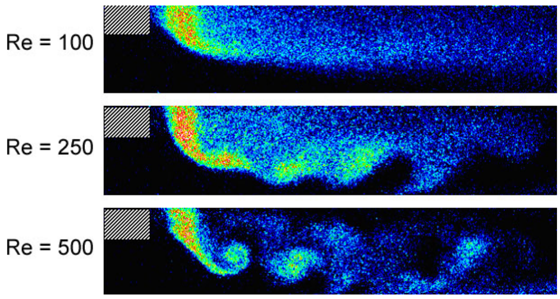

Fig. 8b : Flow images with turbulence promoters upstream from the injection

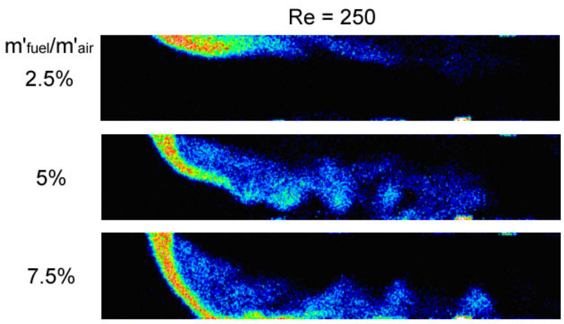

Fig. 8c : Images for three fuel mass flowrates

Combustion set-up

As a final step of the experimental program, a set up for studying micro-combustion is under development (Fig. 9a and 9b).

Different configurations of combustion chambers will be tested. These micro chambers will be located within a pressurized vessel and cooled by a nitrogen flow. The pressure in the combustor will be imposed by the pressure in the vessel. It will be possible to have a mass flowrate of air, with or without premixing with fuel, at a controlled temperature, in order to simulate the thermal effect of the compression in a real micro-turbine.

The objective of this experiment is to study the combustor stability, to measure the mean gas temperature in the combustion chamber, heat losses and combustion efficiency.

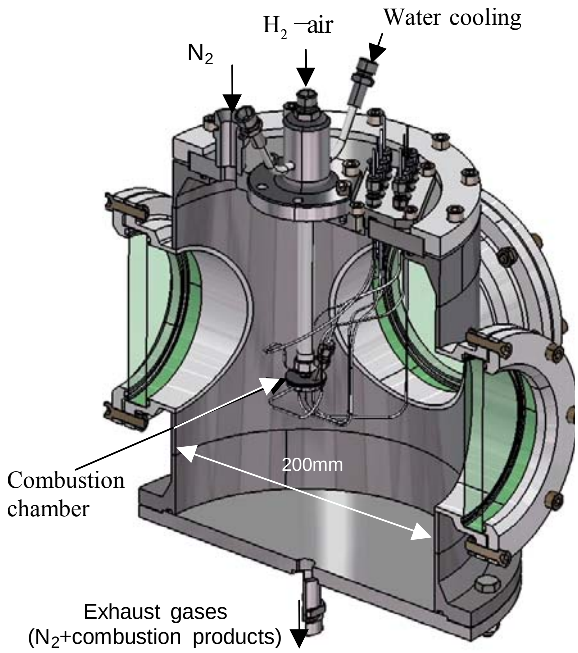

Fig. 9a : Set-up for combustion tests

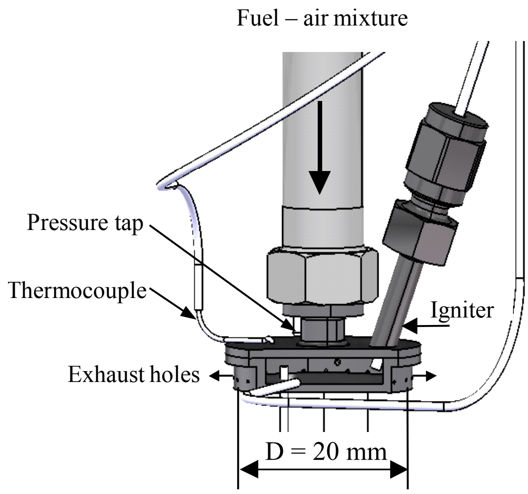

Fig. 9b : Combustion chamber

These parameters will be deduced from future experiments and different methods will be used :

- classical techniques for temperatures measurements (thermocouples, IR camera),
- optical diagnostics, like spontaneous Raman scattering, in order to determine the main species concentrations of the burnt gases at the micro-combustor outlet.

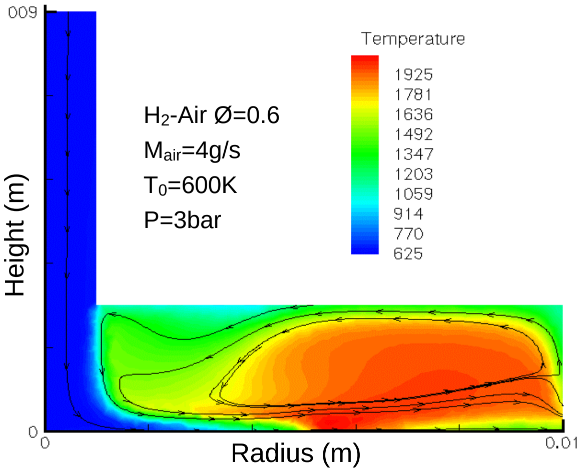

Fig 10 : Computation of gas temperature in the combustion chamber (CEDRE)

Fig. 10 shows a CFD simulation of the gas temperature map in a cross section of the first combustion chamber which will be tested experimentally.

Alternative design

Previous studies (0D and 3D computations, the self ignition problem in the premixed channel, internal heat transfer) have led us to propose an alternative gas turbine engine design in order to avoid some of the possible difficulties.

An efficient way to manage heat losses, may to reduce the surface/volume ratio of the combustor by separating the micro-turbine from the combustion chamber (Fig. 11). This combustion chamber concept, without fuel/air premixing, enables also to avoid self ignition upstream the chamber.

However, the injection system has to be adapted in order to provide good mixing and large recirculation zones to stabilize the flame. In addition, this principle moves away the compressor/turbine from the combustion chamber.

As a result, the engine compressor will be cooler and then its efficiency should be better. On the contrary, the turbine remains hot and has the same or even better efficiency than in the primary MIT design.

Of course, this kind of design should be evaluated in details to estimate its potential concerning the combustion chamber, the turbine and compressor efficiencies.

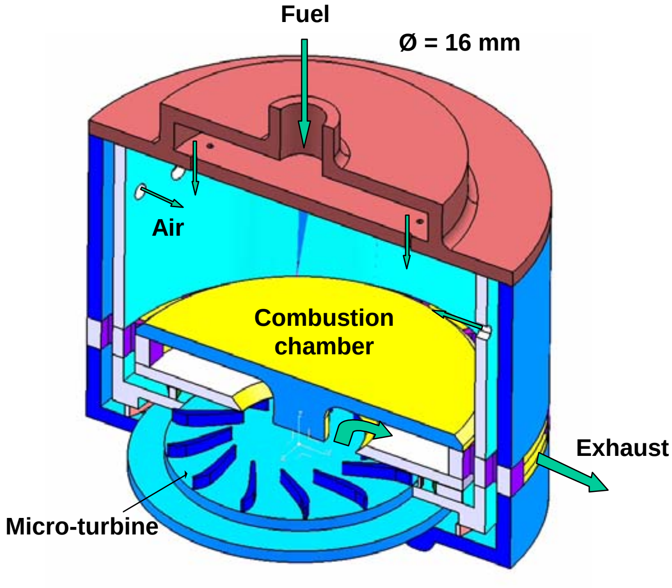

Fig. 11 : Alternative design of micro-turbine (external diameter : 16 mm)

Concluding remarks

The micro power generation is at a feasibility stage. The miniaturization of large scale devices induces many problems like fluid flow in micro channels, combustion in small volume, design, manufacturing etc. The efforts to overcome these problems are sustained by the goal to develop a micro device with a specific energy around 10 times larger than current batteries. In addition, the application field of micro generators is very large (power sources for portable electronics, robots, micro-drones, different electrical supplies…) and will concern many industries.

Presently, it is difficult to say which concept of micro-motor or micro-generator will be the best. But, these kinds of studies, developed for the micro-turbine, can be used for various concepts, especially if the micro-device is based on combustion.

In conclusion, the development of micro-energetic systems requires an important investment in disciplines like fluid mechanics, heat transfer, combustion, electromagnetic systems, materials, sensors, micro-machining, etc.

The success of this project will largely depend on the resolution of the problems previously mentioned in this paper and will require time and obstinacy of different interdisciplinary research groups of working together.

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