Solution of idle LBO problem for high FAR aero combustor

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Abstract：The paper sheds light on the idle lean blow off（LBO）problem for high fuel air ratio（FAR）combustor，which is impossible to be addressed with traditional aero combustor design. A significant improvement in aero combustor design is required to resolve the idle LBO issue. The authors detailed a practical and efficient solution，which not only solved the idle LBO issue but also defined the aero-thermal design for high-FAR combustor. The design will usher in a new era of aero combustor.

Key words：Aero engine；Combustor；Idle lean blow off；High fuel air ratio；Concentric circle zoning combustion

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1 Introduction

From the perspective of technology development，what is the next-generation aero-engine combustor for the fighters？ As stated in Ref.[1]，the main characteristic of future military aero-engine combustors is high Fuel Air Ratio（FAR）.

For instance，combustor with an FAR of 0.051，requires non-visible smoke in the maximum operation，as it is a military engine. For this reason，it is hoped that the soot concentration inside the liner is low to enable non-luminous flame radiation，which will prevent the liner wall from becoming excessively hot and ensure high combustion efficiency. To meet all of these requirements，the combustion should be stoichiometric，meaning that the FAR should be around 0.068. The combustion air fraction is therefore 75%，as calculated by the stoichiometric equation 0.051/0.068=75%.

The extremely high combustion air fraction will give rise to the idle LBO（Lean Blow Off）problem. It is obvious that the contradiction between non-visible smoke and good idle LBO，is truly essential for high-FAR combustor design and development.

This paper will offer the design solution of the idle LBO problem for high-FAR（such as 0.051）aero combustor.

Don Bahr conducted research over three decades ago[2]. He attempted to solve the idle LBO problem for high temperature rise combustor utilizing traditional combustor design（the same meaning as high-FAR combustor）. Don Bahr was a seasoned aero combustor designer and former GE combustion chief. He performed a problem analysis and designed the combustor with an FAR of 0.047. In order to avoid visible smoke，he drastically increased the combustion air fraction. The problem of idle LBOs could not be solved. He examined many ways，including idle condition fuel staging and even variable geometry air swirler，but none of these methods worked. However，his work is classic. It is the first time an aero combustor designer attempted，though failed，to solve the idle LBO problem for a high-FAR combustor.

The conclusion drawn from Don Bahr's work is：

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When the combustion FAR is 0.051 with a very high combustion air fraction, conventional combustor design cannot be adopted to address the idle LBO problem.

2 Reason analysis on the LBO problem

It is vital to briefly review the fundamental principles of conventional aero combustor design in order to comprehend why they cannot resolve the idle LBO problem for high-FAR combustor. The conventional design of an aero combustor can be summarized as follows[3]:

(1) Combustion air enters the liner by a separate flow channel. A small portion is from fuel nozzle air swirler. Additionally, a small portion comes from pre-filming air blast atomization air. Dome cooling air will contribute to combustion. On liner, there are primary air holes;

(2) Typically, it is assumed that half of the air traveling through the liner's primary holes will recirculate and participate in combustion (in real world, less than half). It can also be assumed that half of the cooling air upstream of the primary bore will contribute to combustion;

(3) The pilot fuel is injected through pressure swirl atomizer. The main fuel is generally injected through pre-filming air blast atomizer (a injector which uses a swirl to form a uniform fuel film and spread on the tail edge of a Venturi tube, and shear atomizes under the aerodynamic action of strong swirl and high-speed flowing air), which is very close to the pilot fuel. They share the combustion air. No distinction is made as to which air is for pilot fuel and which air is for main fuel.

Therefore, the whole liner only has one combustion zone, which is called primary combustion zone. To aid with idle LBO and high altitude ignition, combustor designers always make the primary combustion relatively rich. This is called rich primary combustion design. Simply giving less air to primary combustion zone is beneficial to addressing the idle LBO problem. Because when FAR is low, for instance, when main fuel is not working (in the idle condition), there is too much combustion air, so a large portion of combustion air is useless and becomes a burden. In the idle condition, both the fuel air ratio and the fuel flow rate are very low, and the amount of air required for combustion is actually rather minimal. Therefore, the whole primary combustion is richly designed, and helps to solve, to a certain extent, the idle LBO problem. However, the combustion process was unable to fully complete in the primary combustion zone, so a secondary zone (or intermediate zone) shall be designed to allow for further combustion, and secondary air holes are added on liner. The efficiency is typically around 80% at the primary combustion zone exit. Combustion has almost reached its end at the secondary zone exit. With rich primary combustion, it is possible that conventional aero combustor enables acceptable idle LBO.

Rich primary combustion, however, will inevitably result in a significant concentration of soot in the liner and frequent visible smoke. Historically, US fighter engines were renowned for the dark smoke. For instance, GE J79-17A, a very popular fighter, produced black smoke (it became invisible smoke after GE J79-17A was modified to GE J79-17C. At the same time, combustor overhaul life was increased from 600 h to 1 200 h).

There was a Turbojet-6 in our family of aero combustor engines. It had visible smoke and its overhaul life was 200 h. With no modifications during its lifetime before it was decommissioned, it is an example of our fighter aero combustor at the early stage.

For several decades, aero combustor FAR had been going up continuously. Meanwhile, combustor technology had been progressing steadily. Therefore, in a period of time, fighter engine aero combustor had no visible smoke (such as GE J79-17C) with acceptable idle LBO.

However, as the combustor FAR continued to grow, the combustor designer found it harder and harder to strike a balance between invisible smoke and idle LBO. For example, when FAR was 0.038, it seemed that there was almost no more room for compromise. As Don Bahr tested, there was no way to reach a compromise at an FAR of 0.047. Therefore, employing a conventional aero combustor design for the aero combustor with an FAR of 0.051 is obviously not conducive to solving the idle LBO problem.

Several decades ago, some aero combustor designers discovered the main obstacle impeding the resolution of the idle LBO problem: in the idle condition, combustion air entering liner is excessive and more than required. In light of this, some researchers studied variable geometry combustor[4-6]. They put a movable sleeve outside of the liner and in touch with the outer surface of the liner. In the idle condition, the sleeve will block primary air holes and open some additional dilution air holes, while at the maximum operation condition, the sleeve moved downwards to open primary air holes and block some dilution air holes. There was a mechanism to enable the movement, but it was complicated in the authors' opinion. Even if it seems like a wonderful idea, it is completely impractical. If, as it should, the sleeve perfectly fits the surface of the liner when it is idle, there should be no air leakage. However, when the liner is hot (and not evenly hot) in the maximum operating condition, the sleeve becomes stuck and is unable to move freely. After many failures in combustor testing (usually it was in a small cylindrical liner), the research on variable geometry combustor, including variable geometry air swirler[7] and other variable configurations[8], were totally ended. Since then, nobody has ever given it another shot. At this moment, if some researchers still want to employ variable geometry combustor for high-FAR combustor idle LBO, the present author would like to say: there is no chance to develop that technology for real high-FAR combustor application. However, the idea - the combustor designer shall limit the air which is joining combustion while the engine is idle - is useful. How to limit it holds the key to addressing the problem.

3 Brand new design idea

It is abundantly evident from the previous discussion that if aero combustor design-developers wish to find a solution to the idle LBO problem for high-FAR combustor, they must abandon conventional combustor design. To prevent visible smoke, the required combustion air fraction for high-FAR aero combustor must unquestionably be greatly increased. Because there is no bargain. It is impossible to continuously use primary air holes and intermediate air holes on liner. For example, when the required combustion air fraction is 75%, if primary air holes are still used, the only possible way that works is: let 50% air pass through primary air holes (half of it will recirculate back to join primary combustion, i.e. 25%), and another 50% pass through dome into liner, so as to enable 75% combustion air. In doing so, however, there is no cooling air now! But cooling air is a must. A high-FAR combustor cannot survive without cooling air. Therefore, the combustor design concept needs to be significantly changed: the primary air holes should be removed, and all combustion air should only enter the liner through the dome (for advanced cooling technology, as presented in Ref. [1]. It is reasonable to assume, liner cooling air is basically not joining combustion). This is indeed a very significant and also an excellent change of aero combustor design. In this case, combustion aerodynamics is totally determined by dome design and makes it much easier to divide pilot fuel combustion air and main fuel combustion air.

From variable geometry combustor research, one thing is evident: in the idle condition, much less combustion air is needed. Therefore, in the new combustor design, when the engine is idle, limiting the pilot fuel combustion air to a necessary amount is sufficient. But there is a contradiction because the whole liner combustion zone still needs a lot more air for the later combustion in the maximum power condition.

It is interesting to notice that some conventional old aero combustor, just by chance, had good idle LBO, such as an FAR of less than 0.005. How was it achieved? The rationale (there was no systematic research, and only some explanation) is that, in these combustors, very probably, the primary air jets had recirculated back: the returned primary air is directed away from the pilot fuel combustion and does not participate in the combustion. Therefore, in the idle condition, pilot nozzle fuel was only burning with the air coming through small fuel nozzle air swirler in such combustors. A lot of air remained inside the liner, but did not interfere with pilot fuel combustion. This has provided the author with some indication that in the idle condition, pilot fuel should burn with its own air, and other air shall not interfere with pilot fuel combustion.

The authors reevaluated the whole combustor design philosophy in an attempt to specify the solution of the idle LBO problem for high-FAR aero combustor. In other words, there shouldn't be just one zone where the main fuel and the pilot fuel burn simultaneously. Pilot fuel-air combustion zone should be separated from main fuel-air combustion zone (just as a younger son's pocket money shall be separated from the pocket money for his elder brother). Some tried radial separation. For example, pilot fuel-air combustion zone is radially at outer position in a liner, while main fuel-air combustion zone is on the inner side of a liner. This is not a mainstream design and is somewhat cumbersome. Finally, the authors have proposed the concentric arrangement. The whole combustor consists of a number of fuel-air modules. Each module has two portions, pilot fuel-air module is at the center while the main air module is arranged as a circle surrounding the pilot fuel-air module. When there is no main fuel flow, the main air's interference with the pilot fuel-air combustion and the quenching impact will both be minimal. This is the basic idea on the solution of idle LBO problem. The specific design is summarized as follows:

(1) All combustion air enters through the dome;

(2) In the idle condition, only pilot fuel is working and burning with its own air in the module;

(3) The main air flows out of the main air module, the outlet of which is a certain distance away from pilot module exit.

For high-FAR aero combustor, the fuel-air module configuration[9-12], designed by present authors, is shown in Fig. 1. It is a direct mix combustion design without any premixing. The central section consists of pilot fuel nozzle, pilot air swirler and main fuel injector. This portion is in and out from combustor air casing (as shown in Fig. 1, D_p). Surrounding it is a main air module, which is fixed on liner dome. It is worth noting that such design is rather similar to a conventional combustor, so it is very easy for installation, because its installation is very similar to that of the conventional combustor. One thing to note is that while main fuel is not injected close to the main air module, main air is injected from the main fuel module. The main fuel is injected at an angle radially outward from the center.

The fuel air module will operate as follows:

(1) When the engine starts with the ignition by pilot fuel injection and igniter;

(2) The combustor will operate with pilot fuel only in the idle condition;

(3) When the power is a little bit higher than that in the idle condition, as pilot fuel supply pressure gets higher, a flow divider valve (will be mentioned later) in the fuel injector between pilot fuel line and main fuel line, will open. The main fuel starts to work. From now on, both fuel nozzles work simultaneously;

(4) The power will continue to grow, when it reaches a medium to high point (about 60% power condition), main fuel will burn in total separation from pilot fuel combustion, and its own combustion zone will be created. Pilot fuel fraction decreases and main fuel fraction increases as engine power rises. At full power, the main fuel will use up the majority of the available gasoline, or roughly 80%.

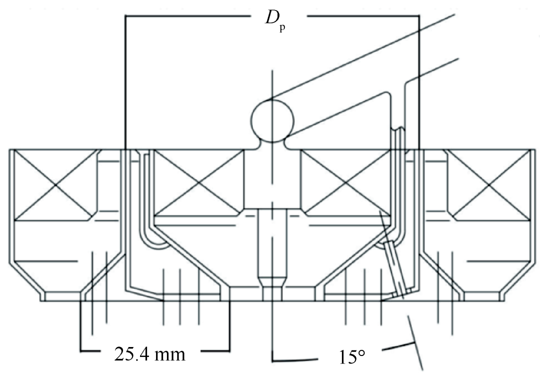

Fig. 1　Fuel-air module for high FAR combustor

It's worth noting that at all operation conditions, pilot fuel nozzle is always working without rest. it is always "on duty". Therefore, there is no meaning to call pilot fuel nozzle as "on duty" fuel nozzle. The main fuel injection is rather special. It is co-axial air atomized plain jet injection instead of pre-filming air blast atomization.

It is well recognized that, for aero combustor, the low power condition operation is always in contradiction with high power condition operation. To solve such contradiction is always an essential part of combustion design. Our main fuel injection design has provided a great solution: in the low power condition, both the main fuel flow rate and injection pressure are low, and the main fuel penetration is not far. Therefore, the main fuel will burn with the pilot fuel combustion, and the flame is stable. The co-axial atomization air is used to prevent overly rich burning of the main fuel. In the high power condition, both the main fuel flow rate and injection pressure are high, and the main fuel penetration is far. The co-axial atomization air helps jets to penetrate farther. As the main fuel is injected in an angle (Fig. 1, it is 15°), in the high power condition, the main fuel will radially spread out to meet main air from main module. They will mix with each other and enable direct mixed combustion.

To accommodate low power operation and high power operation without main fuel staging, our main fuel injection design makes excellent use of the variance in fuel jet penetration with power condition. The main fuel injection angle (15° in Fig. 1) is very critical. For different applications, this angle will be adjusted according to the development needs.

This fuel air module design was initially published in English and was well received by the research community. For instance, the authors accepted the invitation from Nova Science Publisher (in New York state) and contributed Ref.[1]. Another technical note published (at the invitation of an electronic book publisher) earlier (reader shall pay to view the writing). In less than one year, two hundred readers had read the writing. The majority of readers are English speakers, and there are also Russian and Ukrainian speakers. No patent application has ever been submitted, regardless of language. This design is open to use by any aero engine developer.

4 Detailed design

It's worth noting that for high-FAR combustor, such as one with an FAR of 0.051, the idle FAR may be high, such as 0.018.

The design approach for the solution is summarized as follows:

(1) The combustion air fraction is high to keep the combustion stoichiometric in the maximum power condition;

(2) In the idle condition, only pilot fuel works with no main fuel injection;

(3) Pilot fuel-air combustion is designed in the idle condition. This is rather different from conventional combustor design, where whole combustion is designed in the maximum power condition;

(4) In the idle condition, the main fuel does not work, but the main air flows into the liner. How much will this main air quench pilot fuel-air combustion holds the key to the idle LBO. The designer has to make the main air away from pilot combustion in the idle condition with two measures. The first is to put the main air module outlet a certain distance away from the pilot module exit, as shown in Fig. 1. This distance is about one inch. Therefore, in the idle condition, the main air will behave as an observer, and play the role of a standby. The other design is that the main air module allows for swirling air and non-swirling air, with the latter accounting for about one-third of main module air and arranged at the inner side of the main air module. This aerodynamic design will create an air flow pattern where the main air just slips and passes by pilot air recirculation, without mixing with pilot air. Therefore, the quenching effect is weak. This is important to successfully solving the problem of idle LBO;

(5) The pilot air module design is also important. Pilot air is swirling through one axial swirler with a low swirling angle, such as 35°. This also aims to reduce the chance of pilot air mixing with main air. The pilot air will form a relatively small but compact recirculation zone to keep flame stable in the idle condition. Pilot fuel-air combustion is designed at an equivalence ratio of 1.3, because although the design approach has already been adopted to reduce the quenching effect, the main air will still affect the pilot combustion slightly;

(6) The fuel flow rate in the idle condition is known. On the basis of the previously mentioned equivalence ratio of 1.3, the pilot combustion air fraction in the idle condition can be determined. According to previous development experience, it is reasonable to assume the air flow division between the pilot air and the main air in the maximum power condition is the same as it is in the idle condition (it is not exactly correct, but reasonable for the engineering purpose);

(7) The pilot fuel nozzle is a simple pressure swirl nozzle. In the idle condition, flame-out fuel drop size is critical. If the fuel is not at least partially atomized, it is

impossible to keep the flame stable. In the idle condition, the pilot fuel injection pressure drop is very low. Compared to all other types of fuel injectors, the pressure swirl atomizer offers the best drop size at a very low pressure drop condition. In addition, the pressure swirl nozzle has a conical spray which can match with the axial swirler exit air flow nicely. Development experience has demonstrated that a pressure swirl nozzle with a 90° spray angle plus an axial air swirler with relatively low swirling will enable small-scale mixing, which is direct mixed combustion. They make a very good combination and burn well in both low and high operating conditions. It's worth noting that the pilot fuel nozzle is commercially available small nozzle, such as the peanut nozzle from Delavan;

(8) The pilot fuel nozzle injection pressure drop in the idle condition is designed at $0.207\sqrt{f_{\mathrm{idle}}/0.006}$ (MPa). The fuel flow rate in the idle condition is known, so pilot fuel nozzle flow number is determined (here the flow number is in British unit). Under the assumption that in the pilot air fraction in the maximum power condition is the same as that in the idle condition, the pilot air combustion in the maximum power condition is designed to be stoichiometric (whole combustor FAR over combustion air fraction) to determine the pilot fuel flow rate fraction in the maximum power condition (as the total fuel flow rate is known); in the maximum power condition, the pilot fuel nozzle injection pressure drop is determined by another reasonable assumption that the pilot fuel nozzle flow number in the maximum power condition is the same as that in the idle condition. The pressure drop of the main fuel injector is pressure drop of the pilot fuel nozzle minus crack pressure of the flow divider valve. As in the maximum power condition, the main fuel flow rate (total fuel flow rate minus pilot fuel flow rate) is known, the main fuel injector flow number can be determined;

(9) The pilot fuel nozzle injection pressure in the idle condition shall be $0.207\sqrt{f_{\mathrm{idle}}/0.006}$ (MPa) for the following reasons, where f_{idle} means the FAR at the idle condition. It is in onion mode (when the fuel first left the nozzle, it opened up a little, and it seemed to form an atomization cone. However, due to the surface tension, it folds its pockets and becomes an onion.), and there is no atomization. At 0.207 MPa, the spray will change from the onion mode to an opened spray mode, which is beneficial for LBO. It is required to have an idle flame-out FAR of 0.006. In the flame-out condition, the pilot fuel nozzle should still have at least 0.207 MPa pressure drop. The ratio of nozzle pressure drops in the idle condition and in the flame-out condition is proportional to the square of the ratio of idle FAR over flame-out FAR. Therefore, the pilot nozzle pressure drop in the idle condition pressure shall be at least $0.207\sqrt{f_{\mathrm{idle}}/0.006}$ (MPa). If the idle FAR is 0.018, the idle condition nozzle pressure drop will be 1.86 MPa, and probably the crack pressure of the flow divider valve is designed at 2.07 MPa. That means in the maximum power condition, the main fuel injection pressure drop is 2.07 MPa lower than the pressure drop of the pilot fuel nozzle. In view of the main fuel penetration, the main fuel injection angle, 15° as shown in Fig. 1, may need to be modified;

(10) The design of the pilot air module needs to be explained. It consists of one axial swirler and a conical convergent section with an exit. The exit is a metering device. In previous design steps, the amount of the pilot combustion air is determined (expressed as pilot combustion effective flow area, A_{e}). It is worth mentioning that this pilot module $A_{\mathrm{e,req}}$ is the pilot combustion air $A_{\mathrm{e,combustion}}$ minus pilot module cooling air $A_{\mathrm{e,cooling}}$. This pilot air module $A_{\mathrm{e,req}}$ is a required pilot module $A_{\mathrm{e,req}}$. The module inlet swirler $A_{\mathrm{e,1}}$ is designed at 1.8 times required pilot module $A_{\mathrm{e,req}}$. The pilot module exit $A_{\mathrm{e,2}}$ is calculated by the following semi-empirical equation:

$$A_{\mathrm{e,req}} = A_{\mathrm{e,2}} \times \sqrt{1 + (A_{\mathrm{e,2}}/A_{\mathrm{e,1}})^2} \tag{1}$$

Where, $A_{\mathrm{e,1}}$ denotes the pilot module inlet swirler A_{e}, $A_{\mathrm{e,2}}$ denotes the pilot module exit A_{e}, $A_{\mathrm{e,req}}$ denotes the required pilot module A_{e}.

It is worth noticing that the pilot fuel nozzle exit is flushing with pilot module exit, so some area occupied by the pilot nozzle exit shall be considered, and the geometrical diameter of the pilot air module exit is determined;

(11) The main fuel injection is designed in the maximum power condition. It is specially designed with

co-axial air atomized plain jet injection instead of pre-filming air blast atomizer. The atomization air-liquid ratio is designed at two. For liquid injection, as the plain jet is from a section of tube, it is of a certain length (the purpose is to ensure the injection direction). The discharge coefficient is 0.6. For atomizing air, its discharge coefficient is set at 0.64. The number of the main fuel injectors in a module also needs to be determined. The authors' recommendation is that the number of blades be different from that of blades of the main swirler;

(12) The main air module design consists of non-swirling air portion and an air swirler. The non-swirling air accounts for one third of the main module air and is on the inner side of the main module. The swirler has 60-degree swirling, and with non-swirling air, it enables 40-degree swirling of the whole main module air. The design of the main air module is similar to the design of the pilot air module. But the main module has a convergent section, so it is not symmetric. In addition, on the inner wall of the main module, there is cooling air, which is not perpendicular to the inner wall of the main module, but in a totally axial direction.

5 Discussion on flow divider valve

We discuss flow divider valve because it is involved in the next section on whether the main fuel open to work in the idle condition is conducive to addressing the idle LBO problem.

Every fuel nozzle in a conventional aero combustor contains a flow divider valve that separates the pilot fuel line from the main fuel line (with the exception of lean pre-vaporized premixed low-emission combustor with main fuel staging). It is like a non-return valve with a spring. When the pilot fuel line pressure is lower than a certain value, the valve is closed. At a certain pressure level, the valve will open, and this pressure is called crack pressure. If it is higher than this pressure, the fuel will flow from the pilot fuel line to the main fuel line, so the main fuel injector starts to work.

If in an engine, there is only one fuel manifold, and on combustor, the fuel nozzle inlet has only one connector, there is a flow divider valve inside the fuel nozzle.

The flow divider valve has the following three functions:

(1) It controls the power condition in which the main fuel will begin to work;

(2) In the maximum power condition, the pressure drop of the main fuel injector is lower than the pressure drop of the pilot fuel nozzle, creating certain crack pressure;

(3) In the power conditions higher than the main fuel opening condition, it will determine the pilot fuel flow rate and the main fuel flow rate.

In an aero combustor, the flow divider valve is usually integrated inside the fuel injector. However, in some industrial gas turbine engines, the flow divider valve may be separated from the fuel injector. In these cases, there are separate pilot fuel manifold and main fuel manifold, and some flow divider valves installed between these two fuel manifolds. The authors carried out a study with this industrial gas turbine engine manifold with water as the medium (there was no possibility to conduct the study with an integrated manifold). The findings can be summarized as follows:

(1) When the pressure is very close to the crack pressure, there is little liquid leakage over the valve;

(2) The open pressure for different valves varies, and the designer specifies this variation, which should fall within a tolerance range;

(3) Not only the opening pressure of different valves is within a range, but even for the same valve, after multiple opening operations, the crack pressure may differ by around 6 895 Pa. The amount of pressure required to close the valve also varies;

(4) The pressure differential between the pilot fuel line and the main fuel line from the valve opening up to the maximum power condition flow rate is roughly the same as the crack pressure. The fuel division can therefore be determined with the following equation in all power conditions:

$$M_{\mathrm{f}} = N_{\mathrm{m}}\sqrt{\Delta p_{\mathrm{f,pilot}}} \times N_{\mathrm{f,pilot}} + N_{\mathrm{m}} \times N_{\mathrm{j,main}}\sqrt{\Delta p_{\mathrm{f,main}}} \times N_{\mathrm{f,m}} \tag{2}$$

Where, M_{f} denotes the total fuel flow in any power condition, N_{m} denotes the number of modules in a combustor, $\Delta p_{\mathrm{f,pilot}}$ denotes the pressure drop of the pilot fuel nozzle, $N_{\mathrm{f,pilot}}$ denotes the flow number of the pilot fuel nozzle,

$N_{j,main}$ denotes the number of main injectors in a module, $\Delta p_{f,main}$ denotes the pressure drop of the main fuel injector, $N_{f,m}$ denotes the flow number of the main fuel injector.

The pressure drop of the main fuel injector is equal to the pressure drop of the pilot fuel nozzle minus crack pressure of the flow divider valve.

6 Discussion on work of main fuel

Some designer proposed to have the main fuel work in the idle condition. It sounds feasible to let the flow divider valve open before the idle condition, and enable a certain portion of main fuel to enter the liner. For instance, 30% of the main fuel works in the idle condition. When the fuel flow drops, both the main fuel and the pilot fuel drop, but the primary fuel shuts off before the decrease of the pilot fuel and flame-out. However, it is not the case in real terms.

The fact is that, both the air flow rate and the FAR in the idle condition are much lower than those in the maximum power condition. These two factors lead to that the fuel flow rate in the idle condition is much lower than that in the maximum power condition, with the ratio being around ten to one. In the maximum power condition, the main fuel injector always has the majority of the total fuel flow rate of around 80%, whereas the main fuel injector is designed with a fuel flow at 30% of the fuel flow rate in the idle condition. According to equation (2), the fuel flow rate of the main fuel injector in the idle condition is just a small percentage of the main fuel flow rate in the highest power situation. This results in a very unpleasant situation where the main fuel injector's pressure drop in the idle condition is no greater than 6 895 Pa. Therefore, the main fuel is just dripping without any atomization. The reality that the pressure drop of the main fuel injector is within the tolerance range of the flow divider valve presents a more serious issue. As a result, certain main fuel injectors may open to function while others might remain closed. The key concern stems from a fact: a fuel injector won't operate reliably if the pressure drops by only 6 895 Pa. The conclusion is drawn as follows: the design of the main fuel injector open to work in the idle condition is inappropriate from a reliability point of view and is thus not recommended by the authors.

7 Conclusions

The design presented in this paper offers more than merely a solution to the idle LBO problem. In essence, it is an aero-thermal design for a combustion engine (except the advanced compound-angle tangential inlet liner cooling design introduced in Ref.[1]). It is simple, practical and proven effective. The usefulness of other proposals, such as multiple swirler combustion, or trapped vortex combustion (TVC) will not be covered by the authors in this study, because they are far from being adopted in the real design of high-FAR combustors. If there is a simple, practical, reliable and effective design that is almost ready to use, why should we bother with proposals that are only in the preliminary stages of research?

It is interesting that such a fresh aero combustor design is also suitable for not-so-high-FAR military aero combustor. In the maximum power condition, the whole combustion is stoichiometric, sufficient cooling air is ensured and the rest of the air is used for diluting the air. This is a realistic design and will enable an effective aero combustor.

This design also applies to industrial or marine engine combustors and the low-emission combustors of aero engines with high pressure ratios (such as 70 or above).

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高油气比航空燃烧室慢车贫油熄火问题的解决方法 *

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摘 要：本文分析指出传统的航空燃烧室设计不能解决高油气比燃烧室的慢车贫油熄火问题。为了解决慢车贫油熄火问题，需要对航空燃烧室设计作出重大革新。本文详细介绍了一项已被证明是实用且有效的设计，它不仅解决了慢车贫油熄火问题，实际上还阐明了高油气比燃烧室的气动热设计。航空燃烧室设计将进入一个新时代。

关键词：航空发动机；燃烧室；慢车贫油熄火；高油气比；同心圆分区燃烧

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