TECHNICAL NOTE

INFLUENCE OF FUEL ATOMIZATION ON COMBUSTOR LEAN BLOWOUT: AN EMPIRICAL APPROACH

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Abstract

Empirical approach has been adopted to study the effect of operating conditions on atomizing parameters and influence of such parameters on lean blowout limit in a gas turbine combustor. Poor atomization represented by higher spray drop size is found to affect adversely the lean blowout limit. Low air pressure and low fuel temperature results in a higher fuel drop size and require more energy for evaporation and combustion initiation which has to come from more fuel or higher FAR thus raising the blowout limit. Empirical relations can predict reasonably when validated and updated with more and more experimental data.

Nomenclature

C = Specific heat
Cp = Specific heat at constant pressure of air at a mean temperature in the combustion zone
D_p = Prefilming diameter, m
D_h = Hydraulic diameter of atomizer, m
D_r = Mean drop size relative to that of JP-4 fuel
D_o = Initial mean drop size of the fuel spray, m
FAR = Fuel-air ratio through atomizer
f_{pz} = Fraction of total combustor air employed in combustion
H = Heat of combustion
k = Coefficient of thermal expansion of air at a mean temperature in the combustion zone
LCV = Lower calorific value of fuel, J/kg
LCV_r = Fuel heating value relative to that of JP-4
m = Mass flow rate
m_{og} = Oxygen concentration
P_3 = Chamber pressure, kPa
Q = Heat required to vaporize unit mass of fuel
R = Reynolds number
r = Stoichiometric ratio considering oxygen as oxidizer
Tg = Gas temperature (air temperature entering through atomizer)
Ts = Fuel boiling temperature
T_3 = Incoming air temperature, K
U_A = Velocity of air, m/s
V_{pz} = Primary zone volume, m^3
σ = Surface tension of fuel, N/m
ρ_A = Air density, kg/m3
ρ_L = Density of fuel, kg/m3
μ_L = dynamic viscosity of the fuel, kg/m-s
λ_{eff} = Effective value of evaporation constant, m^2/s
λ_r = Effective evaporation relative to that of JP-4

Introduction

The increasingly strict regulations on pollutant emissions have recently led engine designers to develop low-emissions gas turbine engines. To meet this requirement, the lean premixed combustion has shown great reduction in NOx emissions in ground power generation units and also in aero engines [1]. Homogeneous mixing of fuel-air with lower temperature in combustion zone for leaner mixers decreases the thermal NOx emissions [2]. But with

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leaner fuel-air mixture, the reaction rates and flame speed decreases. If the stabilization method is not sufficient to sustain the flame within the combustor, the flame will blowout of the combustor. Flame blowout is always an undesirable phenomena causing expensive shut down of power generation units and also loss of thrust or power in aero engines posing serious safety hazard. Combustor flame-out is a serious concern in highly loaded combustors where the combustion process is ultimately the source of the energy producing the required thrust for aircraft propulsion. When coupled with overall engine system dynamics, flame-out can result in the inability of an engine to recover from a compressor stall event. Flame-out can be catastrophic for a tactical fighter aircrafts engaged in aerial combat. Maintaining a stable flame in the combustion chamber throughout the mission has become a great challenge for a gas turbine engine. This has made understanding the cause of flame blowout very essential for designers and its modeling will be an invaluable tool from operational point of view.

The process of fuel injection which depends mainly on the type of fuel injector employed in the combustor and its design philosophy controls the fuel atomization and its characteristics. To arrive at the combustor blowout modeling, it is important to study the atomizer performance at various engine/combustor operating conditions. Calculation of the evaporation and reaction of the fuel spray in combustion zone needs the evaluation of spray parameters such as mean drop size, drop size distribution and trajectory of the drops. Both empirical and analytical tools are widely used for understanding the combustion process in a practical gas turbine combustor and these tools greatly rely on the accuracy of estimation and or measurement of fuel spray characteristics. In empirical approach, expressions have been derived by researchers based on their vast experimental studies on various combustor configurations [3][4]. These expressions are derived for certain applications with different mode of fuel injection and atomization concepts. Nevertheless, the empirical approach offers simplicity and capability to estimate the combustor performance at various engine power settings. It can be effectively used for different types of fuel with known properties and at different operating conditions. Compared to the empirical approach, analytical models offer promising results by matching the details of spray characteristics with reasonable accuracy. For understanding the influence of fuel atomization on combustor lean blowout limit, an attempt has been made using empirical approach. It is found that operation at low air pressure and low fuel temperature increases the spray drop size which in turn increases the lean blowout fuel-air ratio (FAR) limit. The lean blowout limit will be further studied using analytical tools. This will help to set the base-line boundary conditions and the values generated can be treated as reference.

Hardware Configuration

In this study an annular combustor has been considered which consists of a short pre-diffuser followed by a dump diffuser. The flame tube is provided with a number of equi-spaced airblast atomizers and each atomizer is surrounded by axial flow straight vane air swirler. The advantages of the air-blast atomizers are that the combustor outlet temperature pattern is not affected by the change of the fuel mass flow rate, the temperature of the combustor liner is lower, and the smoke emission is relatively less at high power settings. However, it has the disadvantages of narrow range of combustion stability and poor atomization quality at take-off or altitude relight, which is due to the very low velocity of the air flowing through the combustor dome, so that the relative velocity between fuel film and air is very low causing a poor shearing action of air stream on the fuel film.

Flame tube front end consists of smoothly shaped cowl structure that guides the necessary core airflow inside the flame tube. In combustion chamber air enters the recirculation zone through various apertures in the liner wall. The essential feature, as far as the stabilization process is concerned, is the toroidal flow reversal that is created and maintained by air entering through swirl vanes located around the fuel injector on the dome assembly and through a single row of holes in the wall of the liner as shown in Fig.1. The design of dome assembly, air swirler configuration and the flow field structure in combustor, especially in the primary zone are also equally responsible for proper fuel-air mixing which is essential for better atomization that in turn limits the lean blowout [5]. A schematic layout of an airblast atomizer is shown in Fig.2.

In addition to its main role as the heat-release zone of the combustion chamber, an important function of the primary zone is to re-circulate burned and burning gases to mix with the incoming air and fuel. By this means a mechanism of continuous ignition is established, and combustion can be sustained over wide ranges of pressure, velocity, and fuel-air ratio. For the initiation of ignition, igniters have been inserted through separate holes made in the plane of primary zone and protruding inside primary zone at convenient locations so as to facilitate smooth ignition at sea level as well as at altitudes.

Atomizer Performance

The atomization process of liquid fuel and evaporation rate are the key parameters that control the performance of a gas turbine combustion system. Fuel spray droplet size, its radial and circumferential distribution, spray cone angle and dispersion in the combustion zone are the major characteristics of the fuel injection system which depend mainly on the type and design of the atomizer employed in the combustor. The mean drop diameter of fuel drops is known as Sauter mean diameter (SMD) which is defined as the diameter of a drop within the spray whose ratio of volume to surface area is the same as that of the whole spray. In an airblast atomizer, the drop size can be a function of fuel and air properties at operating condition and the dimension of flow passages [6].

The expression for SMD as derived by Rizk [6] and El-Shanawamy and Lefebvre [7], based on their experiments on airblast atomizers at different operating condition is given by,

$$\mathrm{SMD} = (1+\mathrm{FAR})\,(0.33)\,(\sigma/\rho_A D_P U_A^2))^{0.6}\,(\rho_L/\rho_A)^{0.1} + 0.068\,(\mu_L^2/\rho_L \rho D_P))^{0.5})D_h \tag{1}$$

As it is seen, the SMD is a strong function of fuel properties like surface tension, density and dynamic viscosity. These properties are well established for different fuels with respect to operating temperature [8]. The SMD estimated using equation (1) for different operating pressures is shown in Fig.3. In this calculation air and fuel temperatures are also varied in the range from 317 to 600 K and 303 to 350 K respectively as generally experienced in a combustion chamber corresponding to a typical aircraft mission.

The effect of fuel temperature alone on SMD at standard atmospheric condition is shown in Fig.4. At lower fuel temperatures, fuel droplet size increases and it requires more energy for evaporation [9-12]. Hence, at a constant engine power setting, lowering the fuel temperature will adversely affect the flame stability.

Though theoretical estimation of drop size is possible at any combination of operating conditions, simulating very high pressure and temperature as well as change in fuel temperature during atomizer testing in laboratory is not feasible. Therefore, atomizer is tested simulating different pressure drops across it while maintaining air pressure and temperature at standard atmospheric condition. Fig.5 shows the spray mean drop size estimated for different pressure drops across the atomizer along with limited measured values with Jet A1 fuel which shows a similar trend. This shows the efficacy of the empirical approach to predict the atomizer characteristics but with a correlation factor. With a strong databank for an atomizer, the exponents in equation (1) can be re-defined for more accurate prediction. The fuel temperature of 323 K considered for SMD estimation is similar to what is measured during rig testing at the pump outlet location or on fuel manifold prior to the atomizer.

Similar approach can be adopted to study the effect of spray cone angle which is another important parameter. Spray cone angle decides the extent of air-fuel mixing in the combustion zone and is also a strong function of operating pressure. The spray cone angle in the vicinity of the atomizer face widens with an increase in air pressure at a constant FAR. At a downstream location where atomization is complete and droplets are completely airborne, the spray cone angle becomes independent of pressure [6].

Blowout In Gas Turbine Combustors

For homogeneous fuel-air mixtures, flame blowout occurs when the rate of heat liberation in the primary zone becomes insufficient to heat the incoming fresh mixture up to the required reaction temperature [13]. The rate of heat release due to combustion is a function of heating value of fuel, fuel flow rate and burning rate which in turn is a function of temperature and pressure. The heat required to raise the temperature of incoming air is a function of air flow rate, air initial temperature and air velocity. Based on experimental data, Lefebvre [13] has derived the FAR at flame-out condition in gas turbine combustors as

$$q_{LBO} = \left(\frac{A'' f_{pz}}{V_{pz}}\right)\left(\frac{m_a}{P_3^{1.3}\exp(T_3/300)}\right)\left(\frac{D_o^2}{\lambda_{eff}\,LCV}\right) \tag{2}$$

where A″ is a constant whose value depends on the geometry and mixing characteristics of the combustion zone. The initial mean drop size D_o of the fuel spray can be reasonably estimated at any operating condition using equation (1) as explained in the previous section. The rate of evaporation of a single drop is calculated using the expression given in equation (3) derived by Godsave [14].

$$m_F = (\pi/4)\,\rho_L\,\lambda\,D_o \tag{3}$$

where λ is the evaporation constant in steady state evaporation in quiescent air and D_0 is the initial fuel drop diameter. To account for the adverse effect of the heat-up period and beneficial effect of forced convection, the evaporation constant is modified and effective evaporation constant is defined as follows [13];

$$\lambda_{eff} = \frac{8\,(k/Cp)_g\ \mathrm{In}\,(1+B)}{\rho_L}\,(1 + 0.22\,R_{Do}^{0.5}) \qquad (4)$$

where B is the mass transfer number defined by spalding [15] as

$$B = \left\{ m_{og}\,(H/r) + C(Tg - Ts) \right\} / Q \qquad (5)$$

For fuel with chemical formula of $C_{12}H_{24}$, the balanced chemical equation gives a m_{og} of 3.4286. With proper assumption of mean temperature and air fraction employed for combustion in primary zone, the effective evaporation rate is calculated for a given primary zone volume. The measured combustor global FAR is plugged into the empirical relations to determine the constant parameter. Validation and refinement of the empirical relations can be further made with more and more experimental data. The effect of air pressure on blowout studied using equation (2) is presented in Fig.6. Increasing operating pressure lowers the lean blowout limit and the limit is widened further with higher temperature as shown in Fig.6.

As the fuel temperature decreases, this is generally the case with aero engines gaining altitude, the lean blowout limit increases as shown in Fig.7 making the stable operating range narrower. Drop in air temperature with altitude further deteriorates the blowout limit in aero gas turbine engines. In actual situation, all the three controlling parameters, i.e., pressure, temperature and fuel temperature keep on varying during a flight and therefore need to be studied together.

Since most of the preliminary works were carried out with JP-4 fuel, the equation (2) has been amended suitably to predict the blowout condition when any other fuel is used. This has been achieved by replacing $A'' f_{pz}$ by A' and normalizing the fuel properties. The value of constant A' depends on the geometry and mixing characteristics of the combustion zone. For a measured values of FAR at blowout, i.e., $q_{LBO} = 0.004$, A' is obtained as 0.02735 which is well comparable with other combustion chambers studied by Lefebvre as presented in Table-1 [16].

Table-1 : Comparative Value of Constant A′ in Blowout Equation [16]

Engine	A′
J79-17A	0.042
J79-17C	0.031
F 101	0.032
TF 41	0.013
TF 39	0.037
J 85	0.064
TF 33	0.025
F 100	0.023
Engine under study	0.02735

The effect of air velocity on lean blowout limit can be treated in two ways, i.e., the effect of velocity of air jet through the atomizer that carries the fuel droplets and the effect of air velocity that enters the combustion zone and participates in combustion process. Increasing the jet velocity through the atomizer helps in reducing the drop size as shown in Fig.8. The trend of SMD variation with respect to the air velocity through the atomizer is similar to that predicted by Lefebvre [16]. As SMD increases higher fuel-air ratio is to be maintained to have a stable flame as it is evident from Fig.9.

The trend in the variation of blowout FAR with respect to the fuel mean drop size is similar to that achieved by Rizk [6]. Higher SMD is a result of low air pressure and low fuel temperature as shown in Figs.3 and 4, usually encountered during altitude operation. Larger drop sizes require more energy for evaporation and combustion initiation which has to come from more fuel or higher FAR.

The velocity of air entering the combustion zone can be varied by changing the passage areas and or by changing the size and number of holes in the frontal part of the combustion chamber. Though, the blowout relation used in this study does not account for the velocity directly, it has been dictated by the air mass flow and pressure indirectly.

Conclusion

With limited experimental data available, the empirical approach is found very effective in characterizing the atomizer performance and their influence on flame blowout. It is a tool for parametric study and for understanding the global effect of atomization. However, detailed analysis will be required for more complex fuel injection systems in advanced combustors. This study further re-establishes some of the important behavior of fuel atomization and their effect on blowout which can be summarized as;

- Fuel drop size is a strong function of air pressure and fuel temperature. Low air pressure and low fuel temperature result in higher drop size.
- Higher air temperature and fuel temperature are found to be beneficial in widening the lean blowout limit.
- Poor atomization represented by higher spray drop size requires more energy for evaporation and combustion initiation and increases the lean blowout limit.

Although empirical expressions can provide reasonably accurate predictions of atomizer performance and blowout, they should be validated and updated with large experimental data. This will make them suitable for application in domains where experiments are not generally feasible. Also for analytical studies, this will help to set the base-line boundary conditions treating the values as reference.

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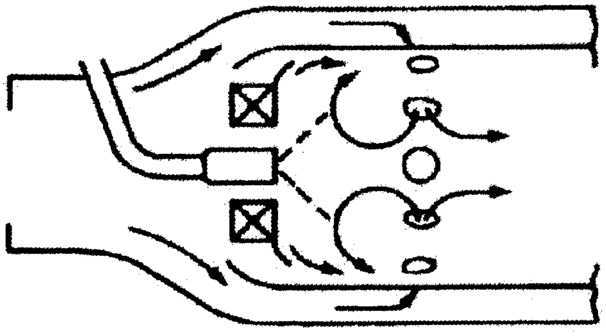

Fig.1 Primary Zone in Annular Combustors

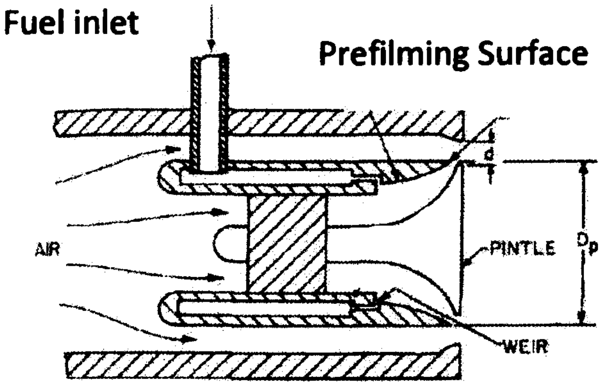

Fig.2 Airblast Atomizer - Schematic

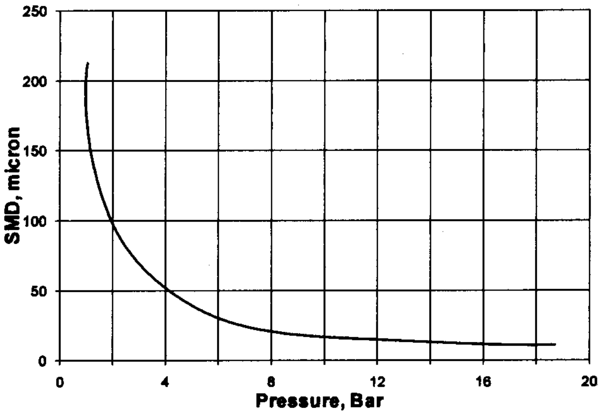

Fig.3 Variation of Mean Drop Size with Operating Condition

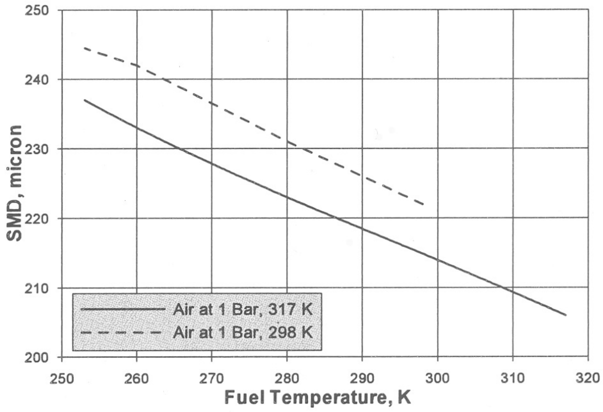

Fig.4 Effect of Fuel Temperature on Mean Drop Size

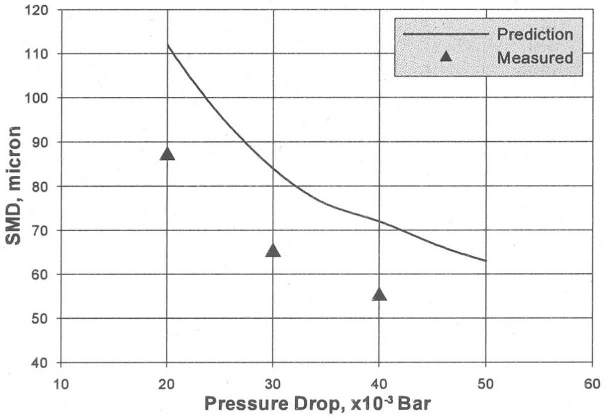

Fig.5 Effect of Atomizer Pressure Drop on SMD at Air Pressure = 1 Bar, Air Temperature = 298 K and Fuel Temperature = 232 K

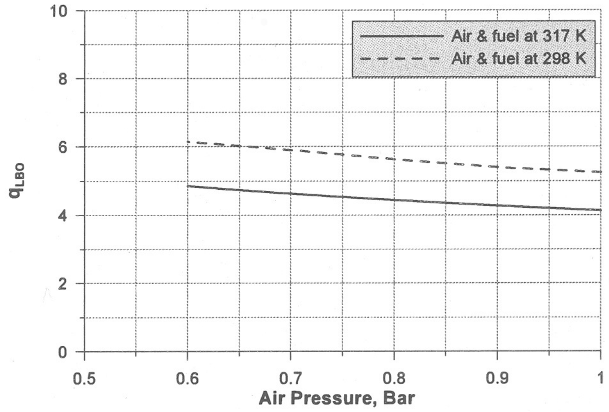

Fig.6 Effect of Operating Pressure on Lean Blowout Limit

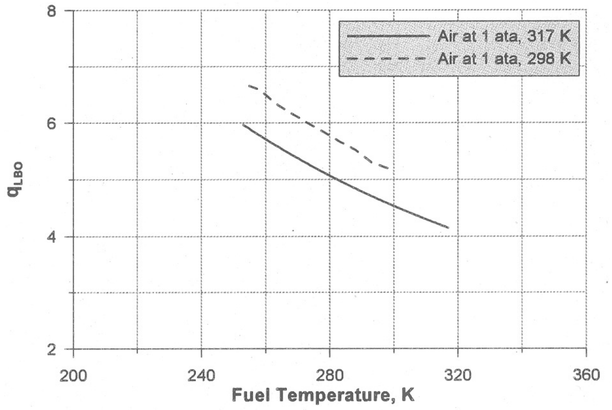

Fig.7 Effect of Fuel Temperature on Lean Blowout Limit

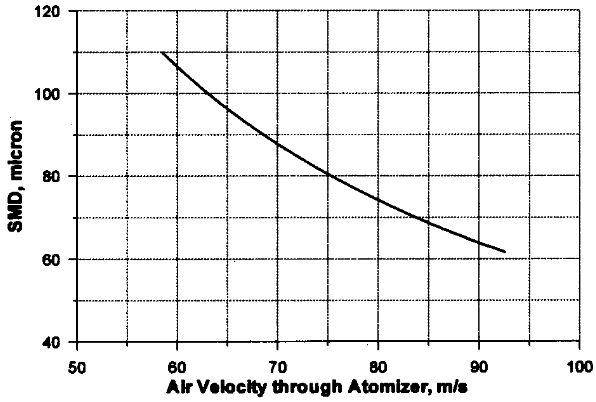

Fig.8 Effect of Atomizer Air Velocity on Fuel Drop Size

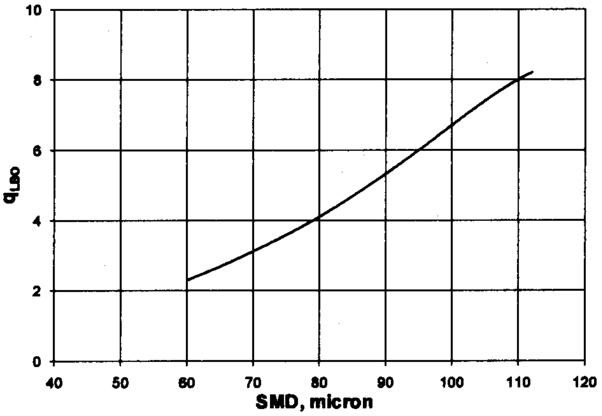

Fig.9 Effect of Fuel Drop Size on Lean Blowout Limit