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# Theoretical Study of Combustion Processes in Aero Gas Turbines for Air Craft Engines

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## Abstract

Combustion process involves various physical and chemical processes which govern and control flames initiation in aero gas turbine engines. During certain flying conditions, at full load, unexpected critical situation may take place in such engines called blow off conditions, which leads to flames diminishing in the combustion chamber of such engines. Gas motion, flow velocity and turbulence kinetic energy are the most important parameters in ensuring flame stabilities. These parameters play a tremendous role and effects on this phenomenon. In gas turbines, the flame exists within a high velocity, non-uniform and intensely turbulent flow field, therefore careful temperature control is vital. Another important factor which must be considered to avoid blow off conditions, is mixture strength. Nearly, all modern gas turbines, due to emissions restrictions, operate on lean mixture conditions which are hard to ignite and lower flame temperatures and thus more risk to reach blow off conditions which leads to a complete flame extinction. These conditions may exist in an air craft engines due to sharp changes in loading parameters, ($\theta_L$): pressure ($P_u$), temperature ($T_u$), mass flow rate ($\dot{m}$), and cross sectional area ($A_u$). At present there is no detailed theory of gas turbine combustion. Therefore, we must resort to simple models and experimental correlations. This paper investigates the blow-off phenomena in aero gas turbine engines, its causes and estimation of required energy to ensure recovery (re-ignition) again inside the combustion chamber. Identifying the conditions at which blow-off takes place and associated loading parameters ($\theta_L$) which are a function of ($A$, $T$, $P$, $\phi$ and $\dot{m}$). The paper also, quantify the recovery conditions (required energy to re-ignition, change in loading parameter ($\Delta q$) Power, Required VHRR: (Volumetric Heat Release Rate) and changes in other loading variables ($\rho$: density, $T$: Temperature, $P$: Pressure, and $\dot{m}$: mass flow rate) tarts with discussing causes of blow off along with effecting operating conditions.

**Keywords**

Blow Off, Re-Ignition, Loading Parameters, Volumetric Heat Release Rate

## 1. Introduction

Gas turbine is a type of internal combustion engine. It has an upstream rotating compressor coupled to a downstream turbine, and a combustion chamber or area, called a combustor, in between. The gas turbine combustor is considered to be one of the most complicated systems in gas turbine design. This complexity arises as the combustor connects the two other main parts, the compressor and the turbine. Turbulent combustion is a complex phenomenon combining the random nature of turbulence with the nonlinearity of chemistry. As a major process for energy production, in particular in propulsion systems, turbulent combustion must be perfectly controlled to ensure maximum efficiency with minimum environmental impact in terms of both fuel consumption and pollutant emissions [1]. Furthermore, a designer of this system requires knowledge involving fluid dynamics, combustion and mechanical engineering knowledge design [2]. Recently, the complexity has increased rapidly because of new requirements of high efficiency, less undesirable emissions and alternative fuels. The designer of a combustion system needs to reach an optimum compromise between all conflicting requirements. These new requirements force researchers to use high levels of computational mathematics like computational fluid dynamics and software to increase the speed and accuracy of design. So; what is meant by blow off phenomena?

Blow-off phenomenal may be defined as the interruption of combustion process, which leads to flame quenching (diminishing). This means no more volumetric heat release [VHHR($q$)] as mixture flow in to the primary zone of GT combustion Chamber) as Loading Parameter ($\theta_L$) changes, on which the loading parameter ($\theta_L$) demonstrates the relative influence of each parameter ($A$, $T$, $P$, $\phi$ and $\dot{m}$). This will result in a sudden drop of power of the engine, which may cause a serious thrust problem.

In literature, the term blow out and blow off were both mentioned in a study conducted by Mansour [3], First one who refers to extinguished flame from lifted starting conditions, where, blow off refers to extinguished flame from attached starting conditions. In this study, concentration will be on blow off conditions. It is important here to mention that flame stabilization is an essential issue to ensure continuous combustion process and that reacting flow recirculation is a critical factor.

Gas turbine combustion is somewhat different to that found in spark ignition engines. In the latter, combustion is transient, usually consists of a propagating flame front, and pressure and temperature varies throughout the combustion event. However, conditions prior to combustion do not vary greatly and the short duration of combustion results in few problems due to excessive heat generation.

In gas turbines, combustion is continuous and careful temperature control is vital. The flame exists within a high velocity, non-uniform and intensely turbulent flow field. Before combustion can even take place, fuel atomization, evaporation and mixing must be success often there is no discernible continuous flame front. Instead, combustion takes place in a near homogeneous volumetric reaction zone. Starting pressures and temperatures can vary enormously since ignition can take place in a cold engine at ground level, or in a hot one at altitude. At present there is no detailed theory of gas turbine combustion. Therefore, it is necessary to resort to an effective models and experimental correlations. The design process of combustion chambers for gas turbines is complicated task and requires careful thinking and managing, in order to obtain an optimum design with high efficiency with low emissions engines [4] [5] [6] [7].

The combustor is a very important component or area of a gas turbine where combustion takes place. It is also known as a burner, combustion chamber or flame holder. In a gas turbine engine, the *combustor* or combustion chamber is fed with high-pressure air by the compression system. The combustor then heats this air at constant pressure. After heating, air passes from the combustor through the nozzle guide vanes to the turbine.

Combustion chamber has the difficult task of burning large quantities of fuel, supplied through the fuel spray nozzles, with extensive volumes of air, supplied by the compressor, and releasing heat in such a manner that the air is expanded and accelerated to give a smooth stream of uniformly heated gas at all conditions required by the turbine. This task must be accomplished with the minimum loss in pressure and with the maximum heat release for the limited space available.

It has been postulated that blow off is avoided by operating the combustor with a wide safety margin from the somewhat uncertain stability limit (*i.e.*, at higher equivalence ratio). Reduction in this margin can potentially result in lower pollutant emissions and enable faster engine transients. The ability to sense blow off precursors can therefore provide significant payoffs in engine reliability and operability, in enabling optimal performance over extended periods of time, in reducing maintenance costs and extending engine life. It has been demonstrated that blow off stability margins can be monitored through suitable analyses of the flame's acoustic and optical signature [8].

## 2. Combustion Efficiency

To obtain good fuel economy and low pollutants production rates, the combustion chambers of such engines must have high efficiency as much as possible which pushes these engines to the limit of safe operation. An acceptable model of gas turbines combustion suggests that

$$\text{Time to burn} = \text{time of fuel evaporation} + \\ \text{time for mixing fuel with air} + \text{time for chemical reaction.}$$

Since the time available for combustion is inversely proportional to the air mass flow rate, the combustion efficiency can be defined by:

$$\eta_c = \frac{\text{time avaiable}}{\text{time required to burn}} \tag{1}$$

$$\eta_c = f\left(\frac{1}{\text{air flow}}\right) * \left(\frac{1}{\text{evaporation rate}} + \frac{1}{\text{mixing rate}} + \frac{1}{\text{reaction rate}}\right)^{-1} \tag{2}$$

The limiting parameters in the above model depend on operation conditions during the transition from ideal to a full thrust.

$$\eta_c = \frac{\rho_g A_f u_t C_{pg} \Delta T}{(FAR)\dot{m}_A \Delta h^o} \tag{3}$$

where $FAR$ is = fuel Air Ratio;

By definition, $C_p \Delta T = (FAR)\Delta h^o$, this gives

$$\eta_c = \frac{\rho_g A_f u_t}{\dot{m}_A}$$

From the above equations, it is clear, that combustion efficiency is a function of the density of fuel air mixture, flame area of, turbulent burning velocity, and air mass flow rate.

Based on a simple model of turbulent burning velocity, which neglects Lewis number effects, and a simple expression for the laminar burning velocity, $u_t = f(P, T)$, it has been shown that (Sixth Symbo),

$$\eta_c = f\left(\frac{p3^{1.75} A_{ref} D_{ref}^{0.75} \exp\left(\frac{T_3}{b}\right)}{\dot{m}_A}\right)\left(\frac{\Delta P_L}{q_{ref}}\right)^{0.375} \tag{4}$$

where $b$ is a constant taken to be 300.

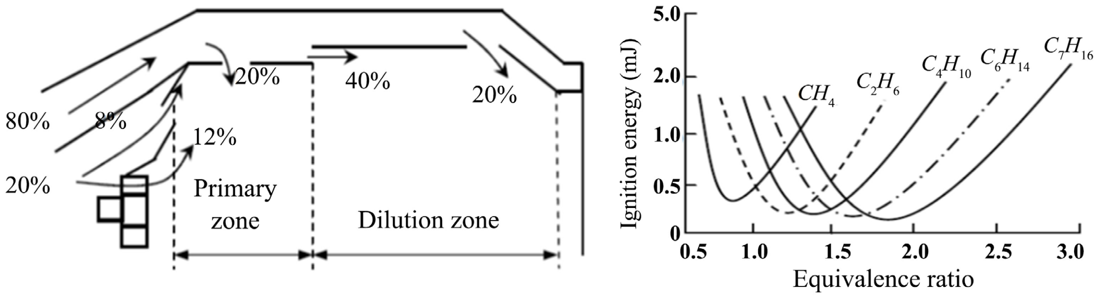
Due to design criteria of combustion chambers for such engines, which is of a sound design, the effect of $(\Delta P_L/q_{ref})^{0.375}$ is small, therefore

$$\eta_{c,\theta_L} = f(\theta_L)$$

$$\eta_c = f\left(\frac{p3^{1.75} A_{ref} D_{ref}^{0.75} \exp\left(\frac{T_3}{300}\right)}{\dot{m}_A}\right) \tag{5}$$

A typical distribution of airflow into a can-contained combustion zone is presented in **Figure 1(a)**, where about 12% of the intake air passes through swirling vanes that surround the central fuel spray nozzle [9]. **Figure 1(b)** shows the minimum external energy needed to initiate a reaction is a function of the equivalence ratio as well as the type of fuel for vaporized fuel-air mixture [10].

At low altitudes flying conditions, the intermediate zone (located after primary zone, will allow for complete burning of any fuel rich pockets. It drops the temperature slowly by addition of air which will allow combustion of dissociated



(a) (b)

**Figure 1.** (a) Combustion chamber flow pattern [7], (b) Minimum ignition energy [8].

CO and other chemical species in the fuel. On the other hand, at high altitudes, pressure will be lower and therefore slower combustion processes. The intermediate zone, in this case, as an extension to the primary zone, provides an increased residence time [11] [12].

So, the so flammability limits would depend on the physiochemical properties of fuel-air mixture, initial conditions, and on the combustion system configuration. Lean blow off occurs when flame speed is lower than the flow velocity of the unburned combustible mixture, and flame stabilization here, is critical issue to ensure continues combustion processes, increase combustion efficiency with well distributed fuel in the primary zone of combustion chamber for such engines. Therefore ensuring high pressure and temperature and lower emissions [13] [14].

## 3. Loading Parameter, ($\theta_L$), in Air Craft Engines

Loading parameter demonstrates the relative influence of the effecting operating variables in gas turbine engines. These variables include: Pressure and temperature changes, density, mass flow rate, flame area, flow velocity, and chemical reaction rates, which eventually will affect the overall values of volumetric heat release rate (VHRR), inside combustion chamber of the engine. Loading parameter can be obtained by applying Equation (5), for a certain operation conditions.

It is an important fact to mention here, that the loading parameter is influenced by changes in the operation conditions. Therefore, this parameter ($\theta_L$), will effect possibilities, whether, blow off and re-ignition will take place or not, and the limits values of these conditions, as well. As a consequence, this will cause fluctuating behavior in the produced energy inside combustion chamber (Volumetric Heat Release Rates—VHRR).

## 4. Estimations of Blow Off (BO) & Re-Ignition (RI) Limits

Many colorations have been applied to estimate the critical values of blow off and re-ignition for a particular turbine. For a given combustor, a simple expression can be obtained to express the volumetric heat release rate, VHRR. **Figure 2** shows an output sample of the computational analysis showing estimated limits

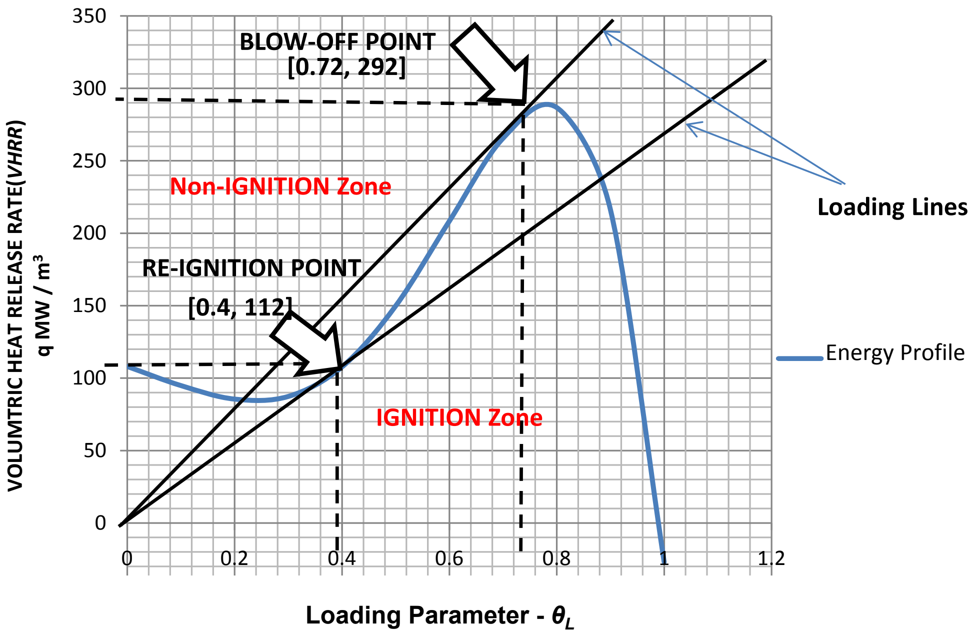


**Figure 2.** Predicted energy profile in combustion chamber for a gas turbine shown limits of BO & RI.

of blow off an re-ignition and the released thermal energy for a certain gas turbine engine.

$$VHRR = total(q\theta) = comb.\ energy + hotwallsenergy = q(\theta)\text{comb} + q(\theta)\text{hotwalls}$$

Sample output of computed results is shown below in Figure 2. The intersection of the loading lines with heat release rates profile, represents operating point. As can be seen from the graph, blow off occurs when these curves no longer intersect.

Blow-off refers to the flame physically leaving the combustor and "blowing out" of the combustor. This issue is often referred to as "static stability", when the flame cannot be anchored in the combustor. However, when the flame velocity increases the flame would blow-off at some point and likewise at the constant velocity and varying equivalence ratio, the flame would also blow-off when the equivalence ratio reduces to a certain value. Some references have related the extinction and the chemical reaction time with Damköhler Number, (the ratio of the residence and chemical kinetic times), and calculated the blow-off time, and hence the blow-off limits, by applying Equation (6).

$$Da = \frac{\tau_{res}}{\tau_{chem}} \qquad (6)$$

Just after Blow-off occurs the walls of the chamber are assumed to be at the Blow-off temp, and mixture continues to flow into the chamber, but at a reduced rate of heat. The combination of this heat energy stored in the hot walls off combustion chamber (given by an empirical correlation in this study: $150(\theta b - \theta)$ MW $m^3$) and energy from previous chemical reactions generated by hot gases from previous combustion process can cause Re-Ignition. It is so important to know all essential properties of the fuel, such as density (kg/m$^3$) at the appropriate $P$ and $T$, Flammability limits ($\phi$), Autoigniiton temperature in air (K), lower heating value (MJ/kg), burning Velocity (m/s) and Stoichiometric fuel/air mass ratio.

**Figure 3** shows Volumetric Heat Release Rates (VHRR, $q$) versus Loading Parameters ($\theta_L$) for different Combustion chamber Designs (A, B, and C). It is quite clear from the graph, that each design is expected to have different values for BO & RI limit values, depending on design criteria for each model. The design process of such combustion chambers is very complicated and requires a very long calculation in order to optimize their performance and minimizing emissions. In fact, it's one of the most common challenges that faces design engineers. Since the approaches depends on empirical correlations derived from previous design experiences.

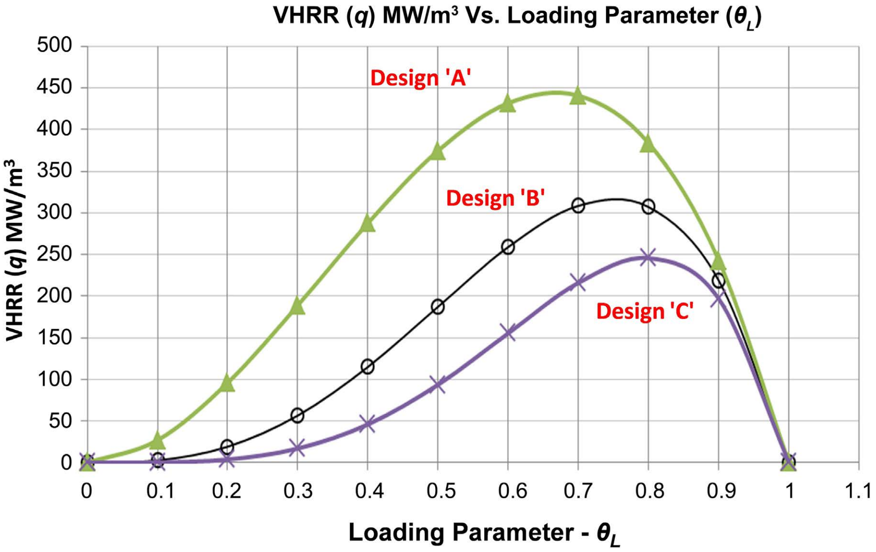


**Figure 3.** Volumetric heat release rates (VHRR, $q$) vs. loading parameters ($\theta_L$) for different combustion chamber designs (A, B, and C).

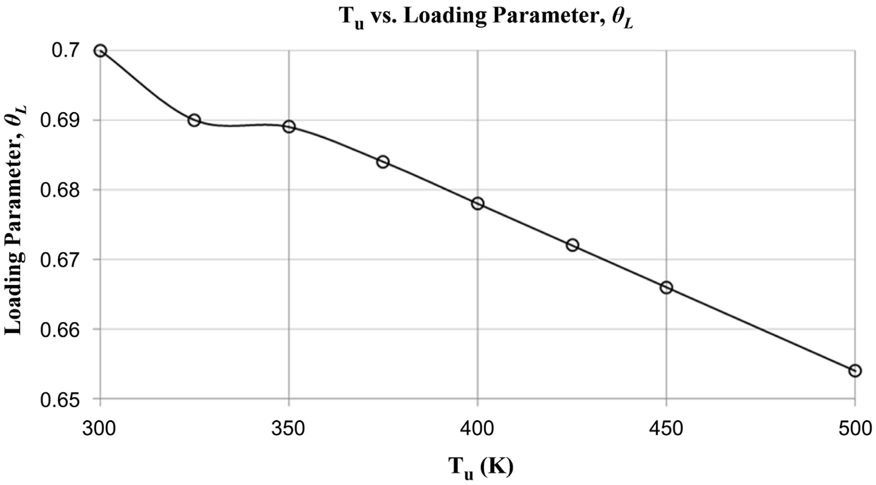


**Figure 4.** Effects of initial temperature on loading parameters ($\theta_L$).

Shown in Figure 4, variations of loading parameter, $\theta_L$, with changes of initial temperature, $T_u$. It's quite clear that it decreases with increasing initial temperature. This due to the increase of heat flux inside the combustion chamber from previous burned charges at high pressure and temperatures associated with elevated temperature at initial conditions.

## 5. Conclusion

The paper investigates combustion processes in aero gas turbines engines with emphasis on combustion efficiency and method of estimating limits of blow off and re-ignition conditions in such engines. Different approaches was used to predicate blow-off limits in aero gas turbine engines, its causes and estimation of required energy to ensure recovery (re-ignition) again inside the combustion chamber. Identifying the conditions at which blow-off takes place and the associated load parameters ($\theta_L$).

## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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## Nomenclature

| SYMBOLS | DESCRIPTION |
|---|---|
| $\theta_L$ | Loading Parameter |
| $P$ | Pressure |
| $T$ | Temperature |
| $A$ | Cross Section Area |
| $D$ | Diameter |
| VHRR($q$) | Volumetric Heat Release Rate |
| $\dot{m}$ | Mass Flow Rata |
| $T_b$ | Burned Temperature |
| $T_u$ | Unburned Temperature |
| $b$ | $\theta$ at Blow Off $\theta$ |
| $r$ | $\theta$ at Re-Ignition $\theta$ |
| $\rho$ | Density |