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Suggestion on Axial Staged Mild Combustion considering the variable load

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ABSTRACT

Increasingly stringent regulations limit the pollutant emission of heavy-duty gas turbines over the entire load range from start-up to baseload. Due to the low emission of axial stage combustion technology and MILD conditions provided by the primary flue gas, axial stage MILD combustion is expected to further lower emissions and become more popular. However, the state of MILD combustion is easy to destroy when the load decreases. The load range of MILD combustion is affected by the gas turbine operating strategy and the axial stage strategy.

Therefore, taking the F-class gas turbine as an example, the present study calculated the combustor parameters of two common partial load operation strategies: the IGV strategy and the fuel-only strategy. A staged MILD model is established by Chemkin software, and parametric research was carried out to analyze the effects of pressure, temperature, and mass flow on thermodynamics and chemical kinetics. Subsequently, the fuel and air distribution in the variable load process is studied to achieve MILD combustion in a large load range. Finally, a novel method of re-staged in the secondary stage is proposed, which enables both operating strategies to achieve MILD combustion from 0 loads to baseload.

Keyword: MILD combustion, Axial stage, Variable load range.

INTRODUCTION

Heavy-duty gas turbines will play an increasingly important role in future energy systems due to their small size, high flexibility, and both power generation and power peak shaving function [1]. The design of the traditional gas turbine low-pollution combustion system mostly limits the baseload or partial high load to satisfy the emission. Nevertheless, emissions increase substantially and dramatically as the load declines [2, 3]. Consequently, the low emissions in the full load range are the design direction of new gas turbine combustion systems.

Low pollution is mainly achieved by regulating the NO_x generation rate in the space location and the accumulation in flue time of the combustion chamber

[4]. The axial staged reduces the accumulated amount of NO_x by distributing a part of the fuel to the secondary stage, reducing the residence time of the fuel in high-temperature zones. In the axial staged technology, the primary stage generates a large amount of flue gas, diluting and mixing the oxidant injected in the secondary stage. By controlling the temperature of the mixture to be higher than its auto-ignition temperature, and the secondary temperature rising below the auto-ignition temperature, the second stage satisfies the conditions of MILD combustion [5]. The large dilution of flue gas reduces the oxygen concentration, resulting in a lower temperature and temperature gradient in the reaction zone. The chemical reaction is moderate, preventing the formation of local thermal NO_x, and the appearance is flameless [6]. Hence, combined with the axial stage and the MILD combustion technology, the axial staged MILD combustion (see Figure1) can control the generation rate and accumulation of NO_x both spatially and temporally, promising lower emission [7].

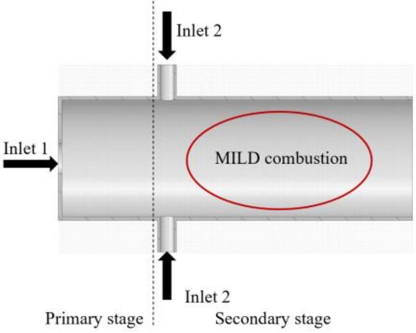


Figure 1. Schematic of Axial Staged MILD Combustion

There are currently few studies on axial staged MILD combustion. Sidey et al. [8] designed a cross-jet MILD combustion experiment for CH4, which is a typical axial staged MILD combustion, but the experiment focused on the relationship between the flame shape and the size of the reaction zone and the oxygen concentration, while did not study the distribution relationship between stages. Zheng et al. [9, 10] established an axial staged CRN model and performed an atmospheric pressure experimental validation, which showed that the fuel distribution relationship and the mixing degree of the primary flue gas and the secondary injection mixture are critical for reducing emissions. Zhao et al. [11] proposed an axial two-stage lean premixed MILD combustor, the fuel is both axial and radial staged, which allows more heat to support secondary premixed gas ignition. At atmospheric pressure, the range of the secondary equivalent ratio is reduced to 0.2-0.5, and the secondary stage realizes MILD combustion of ultra-low emissions. Huang et al. [12] designed an axial staged MILD burner with a swirl primary stage and a cross-jet secondary stage. The swirling flue gas mixing process with the reactants was enhanced. The CRN calculation studied the effect of the staged ratio on ignition characteristics and found that a high staging ratio is conducive to the establishment of MILD combustion. The atmospheric pressure experiments showed that the axial staged MILD combustion can reduce emissions to a lower level. In addition, Sharma et al. [13] proposed a can-type axial staged MILD burner with geometrically induced enhanced internal circulation, and completed experiments with different air injection schemes under atmospheric pressure. The pattern of MILD combustion was observed by OH* chemiluminescence, and NO_x and CO emissions were measured to be below 8ppm and 25ppm, respectively.

According to the above research work, it can be seen that the research on axial staged MILD combustion mainly focuses on the flow conditions and structural forms to achieve a mild environment within a confined load range under atmospheric pressure. However, the gas turbine operates in a high-pressure environment, the combustion chamber pressure and inlet flow change with the change of load, which has a great impact on MILD combustion by affecting thermodynamics and chemical kinetics. At present, there is no literature to study the realization conditions of axial staged MILD combustion in combination with the actual variable load characteristics of gas turbines unit, especially considering the specific strategies. Therefore, this paper takes the PG9351FA gas turbine as an example, establishes a combined cycle variable working condition model, and calculates the parameters of the combustion chamber in the variable load process under two adjustment strategies. Then an axial staged MILD combustion CRN model is established to study the fuel and air distribution of MILD combustion in the variable load. In our previous work, the fuel and air distribution have been shown to be an important factor in realizing MILD combustion under atmospheric pressure experiments [9]. The current study is further present to investigate the possibility of achieving MILD combustion in a large load range using axial staged MILD combustion technology in real gas turbine operation. To achieve MILD combustion from 0 loads to baseload, a re-staged secondary stage method is proposed.

METHODOLOGIES

CONTROL STRATEGIES FOR GAS TURBINE UNITS

The combined cycle model of the gas turbine is not specified in this paper and the establishment of the model refers to the literature [14, 15]. There are many adjustment strategies for variable load units. This paper selects two common strategies including the inlet guide vane (IGV) strategy and the fuel-only strategy, as follows:

1. IGV strategy. The IGV is fully opened to generate the baseload. During the load reduction, the IGV angle is adjusted to ensure the turbine inlet temperature T_3 is constant as the design operating

condition while the turbine exhaust temperature T_4 progressively increases. When the T_4 increases to the maximum value, ensure that the maximum value of T_4 remains consistent, and the IGV angle continues to be changed until the IGV is adjusted to the maximum. Then the IGV angle is retained constant, and only the fuel to be adjusted as the load declines [14]. The IGV strategy is a common regulation method for heavy-duty gas turbines [16, 17].

2. Fuel-only strategy. The airflow remains constant, and only the fuel flow reduces during load reduction.

CRN MODELING OF THE AXIAL STAGE MILD COMBUSTION

Figure 2 shows a simplified axial staged MILD combustion model, directly constructing two sequential PSRs to represent the reaction between the two stages, of which PSR1 represents the primary stage, and PSR2 represents the secondary stage. The total residence time is set to 25ms concerning the typical residence time of gas turbines [7], and each stage is identical at baseload. This model differs from our previous model [9] by omitting the post-flame region of the PFR simulation as emission characteristics are no longer studied. When the mixture undergoes MILD combustion, the temperature field is uniform. Doan et al. [18] investigated the DNS data and found that autoignition is the main combustion mode of MILD combustion. The mixture fraction characteristic scale is similar to the chemical scale, the mixture fraction stratification causes the ignition delayed time gradient, and the reaction kinetics limit the progress of MILD combustion. These characteristics indicate that the PSR model is suitable for simulating premixed MILD combustion. Huang et al. [12] also studied axial staged MILD combustion by establishing two-stage PSRs. The composition and temperature of the mixture enter the CHBR (Closed Homogeneous Batch Reactor). On the reactor temperature versus time curve, the corresponding time of the maximum slop is the ignition delay time τ. Only the composition of the mixture enters the CHBR, given different reactor temperatures, on the maximum rector temperature versus rector temperature cure, the corresponding reactor temperature of the maximum slop is the autoignition temperature T_{si} of the mixture.

The flow rates of air and fuel entering the primary stage are m_{a1} and m_{f1}, respectively. The flow rates of air and fuel entering the second stage are m_{a2} and m_{f2}, respectively. The airflow staged ratio (AR) and the fuel staged ratio (FR) are defined as,

$$AR = \frac{m_{a1}}{m_{a2}+m_{a2}}\ ;\ \ FR = \frac{m_{f1}}{m_{f1}+m_{f2}} \tag{1}$$

The temperature of the Mixer is T_{mix}, and the temperature rise ΔT is the difference between the outlet temperature of PSR2 and T_{mix}. Therefore, when the temperature relationship satisfies the condition: $T_{mix} > T_{si}$, $\Delta T < T_{si}$, the MILD combustion is achieved.

As we all know, the mixing time is generally less than 1 ms in actually staged combustion chambers [19]. In this study, τ is calculated by the full mixing of fuel-air and gas in Mixer under ideal conditions, which is the longest time to ignition. In fact, due to the non-uniformity of mixing, the fuel is in a high temperature gas environment, τ is usually shorter than this calculated. The time scale of flow and chemical reaction are comparable in MILD combustion, i.e., from the perspective of chemical kinetics, it is considered that the τ of the secondary stage mixture needs to exceed 1ms. In order to ensure the combustion efficiency, it is also necessary to satisfy τ < 12.5ms, even if the secondary residence time is large enough, the maximum τ cannot exceed 25ms.

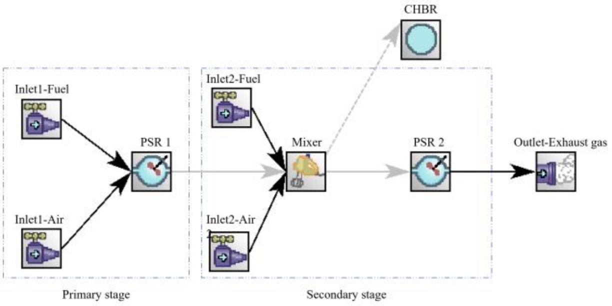


Figure 2. Chemical Reaction Network Model for Axial Staged MILD Combustion

RESULT AND DISCUSSION

PARAMETERS OF VARIABLE LOAD

VALIDATION

The traditional PG9351FA gas turbine is selected as the research object. When it is running at the baseload, the pressure is 15.52 bar and the outlet temperature of the combustion chamber is 1394℃ [20]. Figure 3 shows the comparison between the simulation results and the literature [14]. It can be seen that the simulation results in this paper are consistent with the data given in the literature. Within the error range, the calculation results of variable load parameters are considered reliable.

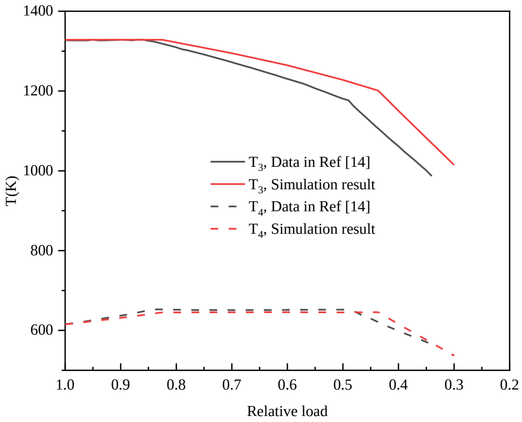


Figure 3 Comparison of the Results with the Ref [14]

PARAMETERS

The operating parameters of the combustion chamber under partial load are shown in Figure 4. In the IGV strategy, the T_4 reaches a maximum and the IGV angle is adjusted to the maximum when the gas turbine load is reduced to 77.4% and 34.94%, respectively. Since then, as the load decreases, the trend of IGV strategy parameters is the same as that of the fuel-only strategy.

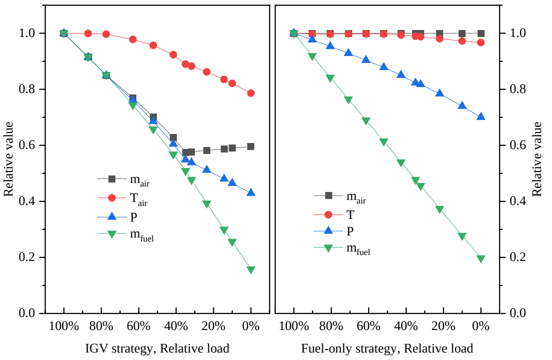


Figure 4 The Parameters of the Combustor in Variable Load

PARAMETERS ANALYSIS

During the Chemkin calculation, the GRI3.0 mechanism file is selected [21]. When calculating the τ and T_{si}, the end time of CHBR is a crucial parameter and is usually set to 1s [5]. It is obvious that the τ is not related to the end time, and only needs to ensure the end time is greater than the τ. Fixed AR=FR=50% and set a range of different end times, the effect of the end time on T_{si} is shown in Figure 5. As the end time increases, the T_{si} decreases significantly. Therefore, it is necessary to think deeply about the definition of MILD combustion considering the effect of T_{si}. As we all know, MILD combustion is initially used in furnace and the mixture's residence time inside the furnace is long enough that the end time set to 1s is reasonable. The T_{si} calculated with a sufficiently long time (1s) and the actual gas turbine residence time are T_{si} and T_{si-a}, respectively. Here, the MILD combustion determined with the T_{si} is defined as general MILD combustion, while determined with the T_{si-a} is defined as special MILD combustion.

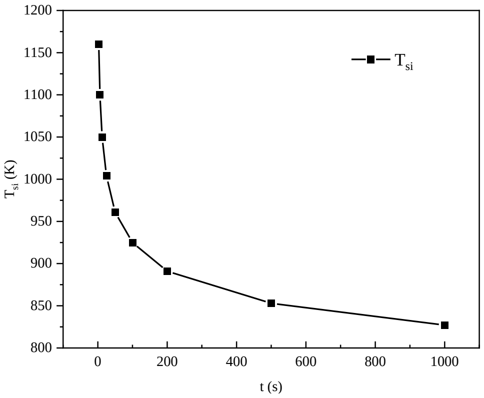


Figure 5 The Effect of End Time on T_{si}

EFFECT OF STAGE RATIO ON BASELOAD

The effects of FR and AR on the combustion state at the baseload are shown in Figure 6. The AR and FR in the red region form general MILD combustion. It can be seen that when the FR is greater than 20%, there is a general MILD combustion region. The minimum value of AR is limited by ΔT and T_{si}, and their relationship can also limit the maximum value of AR at smaller FR. When the FR is larger, fixed the FR, as the AR increases, the amount of primary air increases, resulting in a gradual decrease in the primary equivalence ratio. The AR continues to increase until the primary stage cannot burn (φ_1 represents the primary equivalence ratio), at which point the maximum value of AR is determined by the primary lean burn limit. Compared to the general MILD combustion, the AR and FR in the shaded region form special MILD combustion. Regarding the special MILD combustion, the FR is greater than 37%, and the minimum value of AR is limited by T_{mix} and T_{si-a}.

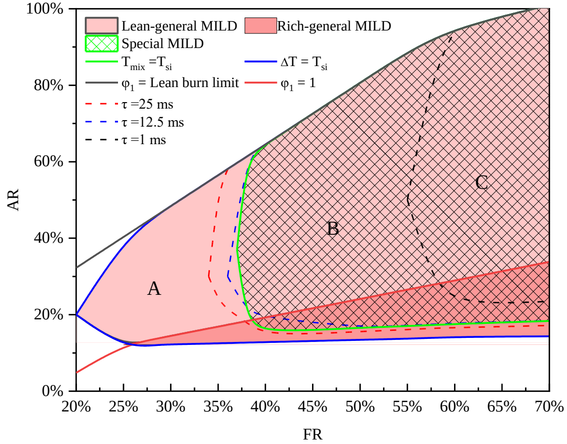


Figure 6 The Effect of FR and AR on MILD Combustion

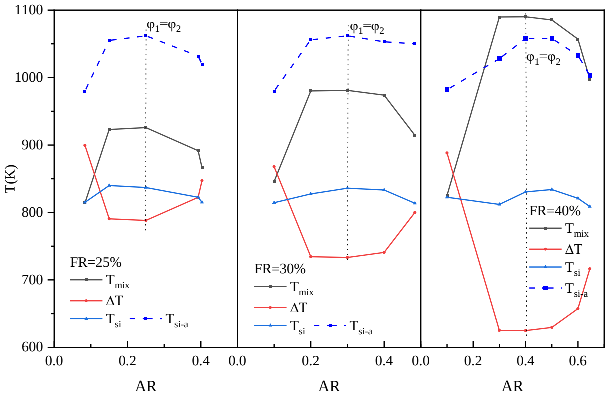


Figure 7 The Effect of AR on T

Figure 7 shows the relationship between temperature and AR at FR = 25%, 30%, and 40%, respectively. The maximum value of AR corresponds to the lean burn limit in Figure 6. When the AR is large, the T_{mix} is much greater than T_{si}, and the ΔT is smaller than the T_{si}. As the FR decreases, ΔT gradually increases (e.g., FR=25%, $\Delta T > T_{si}$), and the critical value of FR is 28.8%. Therefore, the maximum AR is determined by the lean combustion limit at FR>28.8%, and the maximum AR is determined by the relationship between ΔT and T_{si} at FR<28.8%. When the AR is relatively small, the curves of ΔT, T_{mix} and T_{si} intersect. The AR corresponding to the intersection of ΔT and T_{si} is larger, which determines the minimum AR of general MILD combustion. With the reduction of FR, the AR range of MILD combustion gradually decreases. When FR=20%, the ΔT coincides with the two intersections of T_{si}, i.e., general MILD combustion cannot be achieved at FR<20%. Nevertheless, the T_{si-a} is much larger than T_{si}, and it is only when FR is particularly large that T_{mix} can intersect with T_{si-a}(e.g., FR=40%).

According to the primary stage equivalence ratio, the AR range of Figure 6 is divided, and it is found that the area that can achieve lean-general MILD combustion is much larger than that of rich-general MILD combustion. Lean-general MILD combustion can make full use of the low NO_x advantage of the existing lean premixed combustion technology and is more suitable for design baseload. The dotted lines in Figure 6 represent τ=1ms, 12.5ms and 25ms, respectively. It can be seen that the smaller the FR, the larger the τ. When the FR is less than 36%, the entire general MILD burning range of τ is greater than 12.5ms. Especially when the FR is less than 34%, τ is greater than 25ms, i.e., the area A in the figure, the secondary combustion efficiency needs to be paid attention to. In area C, τ<1ms, even if the MILD combustion is satisfied, the τ is too short to organize the flow. Hence, in terms of chemical kinetic, the optimal for achieving MILD combustion is region B (The area is bounded by τ=1ms and τ=12.5ms).

It should be emphasized that the curve τ=12.5ms almost coincides with the special MILD combustion boundary $T_{mix} = T_{si-a}$ as the end time is set to 12.5ms when calculating the T_{si-a} in CHBR. The mixture must stay in the CHBR longer than the τ before the combustion reaction can occur. If the end time is set to a larger value of 25ms, the border of special MILD combustion will move closer to the right of τ=25ms. That is, special MILD combustion is almost essentially the same as general MILD combustion controlled by the τ. Regardless of whether it is reflected in the τ or the T_{si-a}, in actual gas turbine, the influence of chemical kinetic factors on MILD combustion is still very large and must be considered. For convenience, the following text no longer emphasizes the difference between general and special and only uses MILD combustion to represent this technology.

In addition, the dotted line in Figure 7 indicates that the two stage equivalence ratios are the same and equal to the global equivalence ratio. At this condition, the T_{mix} is the largest and the ΔT is the smallest, which is most in line with the temperature relationship of MILD combustion. In summary, for the PG9351FA unit to achieve axial staged MILD combustion, the primary fuel distribution ratio is not less than 20% at baseload, and the higher primary the fuel distribution ratio, the wider range of staging ratio. Taking into account the τ, the fuel air flow distribution needs to be in area B in Figure 6. To achieve lean-MILD combustion, the FR range is 37% < FR<60% and it is the best staged ratio when the equivalences of the two stages are the same.

EFFECT OF DIFFERENT STRATEGIES ON VARIABLE LOAD

The distribution ratio of air flow between stages is determined by the structure of the combustion chamber and does not change. Fixed the τ=5ms at baseload [22] and fixed the primary stage equivalence ratio φ_1 during load reduction process, the comparison under the two control strategies is shown in Figure 8. With the load decreasing, both strategies can always maintain MILD combustion. The T_{mix} and the ΔT remain unchanged until the load reduces to 77.4%, then both gradually decrease with load reduction in IGV strategy. When the load is reduced to the maximum of IGV adjustment, T_{mix} is almost unchanged while ΔT decreases linearly. In contrast, with the decrease of load, the change of T_{mix} and ΔT in fuel-only strategy is the same as that of IGV strategy after maximum regulation. Due to the air temperature is lower in IGV strategy, resulting in the T_{mix} is lower than that of the fuel-only strategy at the same load, and the ΔT is the opposite. Compared to the two strategies, the differences in T_{mix} and ΔT gradually increase with the decrease of load. The effect of this difference is particularly pronounced on the τ.

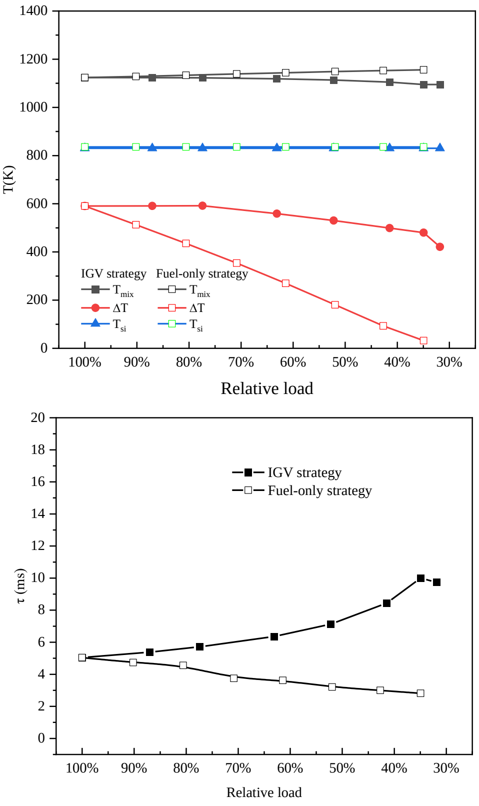


Figure 8 Comparison of Two Control Strategies

The τ increases in IGV strategy while decreases in the fuel-only strategy with the load decreasing. As the τ is related to the pressure, temperature and concentration of reactants, the influence of each parameter on the τ is shown in Figure 9. It can be seen that the τ increases as the pressure and temperature decrease, but decreases as the relative flow of air and fuel decreases. The coupling effect of all parameters results in the increase under the IGV strategy and the decrease under the fuel-only strategy in Figure 8. This shows that in the IGV strategy, the decrease in air temperature causes the drop in T_{mix} that plays a major role in τ. Nevertheless, in the fuel-only strategy, the air temperature change is relatively small that the decrease in the secondary fuel flow is stronger. Comparing the changes of τ, it is found that the IGV strategy has a larger range, while under the fuel-only strategy, the τ decreases more slowly and the relative change in τ is lower than 45%. The change of τ in the process of variable load is as small as possible, which could avoid exceeding the limits.

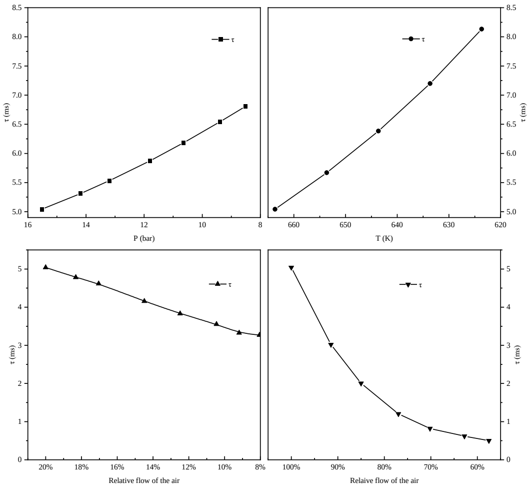


Figure 9 The Effect of Variable Parameters on τ

Since the T_{mix} is the main reason causing the τ increasing, controlling the change in T_{mix} is the best way. As shown in Figure 10, where T_1 represents the outlet gas temperature of primary stage. The temperature of T_1 cannot be increased during the load reductions to avoid overheating and bringing problems to the cooling of the combustion chamber. Compared to the fixed in φ_1, fixing in T_1 attenuates the drop in T_{mix} so that the τ changes more slowly. Since the air temperature gradually decreases as the load drops, the φ_1 needs to be slightly increased to keep the T_1 constant.

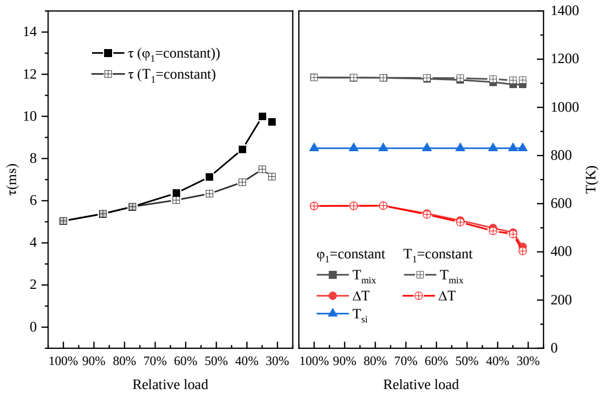
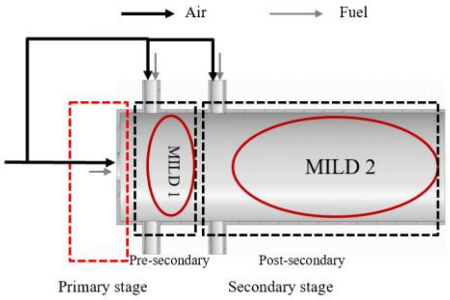


Figure 10 T_1 Regulation in IGV Strategy

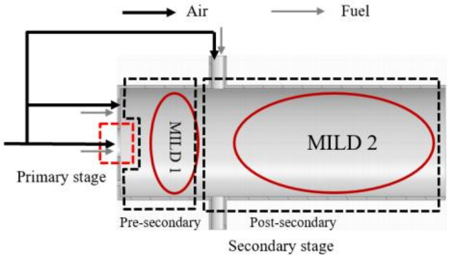
Therefore, MILD combustion can always be maintained in thermodynamical during load drops process, and both strategies can satisfy the limitation of the τ. The minimum value of the load variation range of MILD combustion is determined by reducing the secondary stage fuel to 0. Theoretically, the primary stage forms premixed combustion and the gas entering the second stage is only air acting as cooling air below this load.

As shown in Figure 4, whether in the IGV strategy or the fuel-only strategy, the fuel flow rate is less than 20% at zero load. Combining with Figure 6, it can be seen that if this amount of fuel is used as the primary fuel, it will not only fail to build MILD combustion, but also lead to a particularly large ignition delay time. Therefore, it is considered to divide the secondary stage and discuss the re-staged behaviour to realize MILD combustion from 0 loads to baseload.

The secondary stage is divided into two stages, called the pre-secondary stage and the post-secondary stage, respectively. It is emphasized that the form of re-staged is not limited to the axial (Figure 11a), but can also be radial (Figure 11b) or other forms. The purpose of re-staged is to mix the gas of the primary stage with the pre-secondary stage to achieve MILD combustion in pre-secondary stage, which benefits are more obvious at low loads. At higher loads after a certain load, the gas of the primary stage and the pre-secondary stage are used together to realize the MILD combustion of the post-second stage. The primary stage and the pre-secondary stage are taken together to be essentially the same as the primary stage especially in baseload. In order to maintain the concept of MILD combustion in secondary stage, the mentioned re-staged is named. As above, at baseload, the sum of the fuel distribution of the primary and pre-secondary stages is required to satisfy the condition 37%<FR<60%.



a Axial Re-staged



b Radial Re-staged

Figure 11 The Form of Re-staged in Secondary Stage

The air distribution of the primary stage and the pre-secondary stage is also determined by the combustion chamber structure and remains constant at varying loads. For the above fixed τ=5ms at baseload, the variable load process combined with the primary and the pre-secondary stages should comply with Figure 8. At low loads after the IGV is adjusted to maximum, the IGV strategy is the same as the fuel-only strategy. Therefore, during the entire variable load process from baseload to 0 load, the fuel flow of each stage is shown in Figure 12.

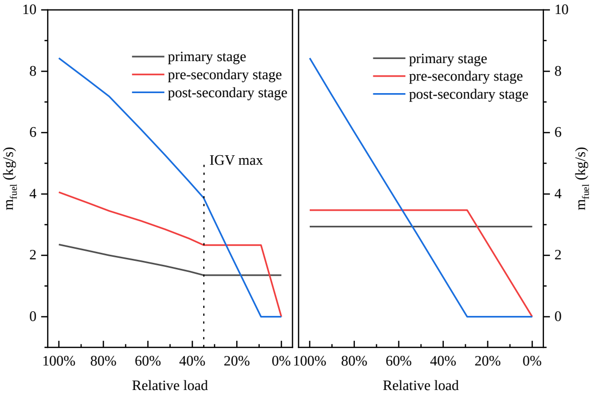


Figure 12 The Flow of Fuel During Variable Load

It is believe that in addition to the other strategies studied in this paper, MILD combustion from 0 loads to full load can be achieved by staging the secondary stage. The difference is that the fuel and air distribution ratio of variable load is different under different strategies. In other words, the load ranges to sequentially adjust the post-secondary stage, the pre-secondary stage, and the primary stage are distinct.

CONCLUSIONS

This paper takes PG9351FA as an example to calculate the variable load operating parameters of the combustion chamber in IGV strategy and fuel-only strategy. Combined with the established CRN model of axial staged MILD combustion, the distribution of the flow of fuel and air in the process of variable load is studied. To achieve MILD combustion from 0 loads to baseload, a method of re-staged is proposed. The main conclusions are as follows:

1. The T_{si-a} calculated by considering the actual residence time is higher than the convention T_{si}. The T_{si-a} and the τ are similar to constrain on MILD combustion. Therefore, both thermodynamics and kinetics need to be considered when designing MILD combustion.

2. The AF and FR are important factors and should be limited within a certain range, where FR should be larger than 20%, but the chemical kinetics requires 37%<FR<60% at baseload. It is the best staged ratio when the equivalences of the stages are the same.

3. In the process of variable load, keeping the primary stage equivalence ratio constant, MILD combustion can be maintained all the time. Under the IGV strategy, it is more advantageous to keep the temperature of the primary stage gas unchanged.

3. By re-staged the secondary stage, the secondary stage of axial staged can realize MILD combustion from baseload to 0 load.

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Suggestion on Axial Staged Mild Combustion considering the variable load

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ABSTRACT

Increasingly stringent regulations limit the pollutant emission of heavy-duty gas turbines over the entire load range from start-up to baseload. Due to the low emission of axial ~~stage~~staged combustion technology and MILD conditions provided by the primary flue gas, axial ~~stage~~staged MILD combustion is expected to further lower emissions and ~~become~~becomes more popular. However, the state of MILD combustion is easy to destroy when the load decreases. The load range of MILD combustion is affected by the gas turbine operating strategy and the axial ~~stage~~staged strategy.

~~Therefore, taking the F-class gas turbine as an example, the present~~The current study ~~calculated~~evaluates the combustor parameters of two ~~common~~popular partial load operation strategies: the IGV strategy and the fuel-only strategy~~.~~, using a F-class gas turbine as an example. A staged MILD model is established by ~~Chemkin~~CHEMKIN software, and ~~parametric research was carried out to analyze the effects~~the notion of ~~pressure, temperature,~~MILD combustion applications in gas turbines is enhanced from both a thermodynamic and ~~mass flow on thermodynamics and chemical kinetics.~~a kinetic standpoint. Subsequently, the fuel and air distribution in the variable load process is ~~studied~~then investigated in order to accomplish MILD combustion over a wide turndown range. Finally, a novel secondary stage re-staged method is proposed, allowing both operating methods to achieve MILD combustion ~~in a large load range. Finally, a novel method of re-staged in the secondary stage is proposed, which enables both operating strategies to achieve MILD combustion from 0~~from zero loads to baseload.

Keyword: MILD combustion, Axial ~~stage~~staged, Variable load range.

INTRODUCTION

~~Heavy~~Due to their small size, great flexibility, and ability to generate and reduce peak power, heavy-duty gas turbines will play an increasingly important role in future energy systems ~~due to their small size, high flexibility, and both power generation and power peak shaving function [1]. The design of the traditional~~[1]. To meet emission requirements, the conventional gas turbine low-pollution combustion ~~system mostly~~technology primarily limits the baseload or partial high load~~ to satisfy the emission.~~. Nevertheless, as the load decreases, emissions increase ~~substantially~~significantly and dramatically ~~as the load declines~~ [2, 3]. ~~Consequently, the low emissions in the full load range are the design direction of~~ As a result, the new gas turbine combustion systems are being designed with low emissions in the complete load range in focus.

Low pollution is ~~mainly~~primarily achieved by ~~regulating~~controlling the ~~NO_x generation~~ rate of NOx formation in the space location and ~~the~~ accumulation in ~~flue time of~~ the combustion chamber flue time [4]. ~~The axial staged reduces the accumulated amount of NO_x by~~ By distributing a ~~part~~portion of the fuel to the secondary stage~~, reducing~~ and lowering the residence time ~~of the fuel~~ in high-temperature zones~~. In~~ , the axial staged technology minimizes the accumulated amount of NO_x. The primary stage of the axial staged technology~~, the primary stage~~ generates a ~~large~~considerable amount of flue gas, ~~diluting~~which dilutes and ~~mixing~~mixes the oxidant injected in the secondary stage. ~~By controlling the temperature of the mixture to be higher than its auto-ignition temperature, and the~~ The secondary ~~temperature rising below the auto-ignition temperature, the second~~ stage satisfies the conditions of MILD combustion ~~[5]. The large~~by limiting the temperature of the mixture to be greater than its autoignition temperature and the temperature rise to be lower than the autoignition temperature [5]. The considerable dilution of flue gas ~~reduces~~lowers the oxygen concentration in the reaction zone, resulting in a ~~lower~~reduced temperature and temperature gradient ~~in the reaction zone.~~. The chemical reaction is moderate, ~~preventing~~which prevents the ~~formation~~generation of local thermal NO_x, and ~~the~~ it has a flameless appearance ~~is flameless~~ [6]. ~~Hence, combined~~As a result, when used in conjunction with ~~the~~ axial ~~stage~~staged and ~~the~~ MILD combustion technology, ~~the~~ axial staged MILD combustion (see ~~Figure1) can control the generation~~Figure 1) may limit the rate of NO_x formation and accumulation ~~of NO_x~~ both spatially and temporally, ~~promising~~resulting in lower ~~emission~~emissions [7].

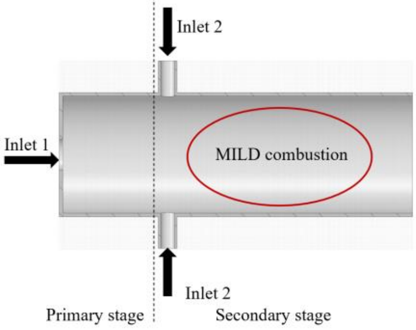


Figure 2. Schematic of Axial Staged MILD Combustion

There are ~~currently few studies~~limited investigations on axial staged MILD combustion at the moment. Sidey et al. [8] designed a cross-jet MILD combustion experiment for CH_4, which is a typical axial staged MILD combustion, ~~but~~however the experiment focused on the relationship between ~~the~~ flame shape and ~~the size of the~~ reaction zone size and ~~the~~ oxygen concentration, ~~while did not study~~rather than the distribution relationship ~~between~~across stages. Zheng et al. [9, 10] ~~established~~developed an axial staged chemical reactors network (CRN) model and ~~performed an~~validated it using atmospheric pressure experimental ~~validation, which showed~~, demonstrating that the fuel distribution relationship and the mixing degree of the primary flue gas and the secondary injection mixture are ~~critical~~crucial for ~~reducing~~lowering emissions. Zhao et al. [11] ~~proposed~~presented an axial two-stage lean premixed MILD combustor~~,~~ in which the fuel is staged both ~~axial~~axially and ~~radial staged, which allows more~~radially, allowing greater heat to ~~support~~be available for secondary premixed gas ignition. ~~At atmospheric pressure, the~~The range of the secondary equivalent ratio is reduced to 0.2-0.5~~,~~ at atmospheric pressure, and the secondary stage ~~realizes~~achieves MILD combustion ~~of~~with ultra-low emissions. Huang et al. [12] designed an axial staged MILD burner with a swirl primary stage and a cross-jet secondary stage. The swirling flue gas mixing process with the reactants was enhanced. The CRN calculation ~~studied~~evaluated the effect of the staged ratio on ignition characteristics and ~~found~~concluded that a high ~~staging~~staged ratio ~~is conducive to the establishment of~~promotes MILD combustion formation. The atmospheric pressure experiments showed that the axial staged MILD combustion can reduce emissions to a lower level. In addition, Sharma et al. [13] ~~proposed~~presented a can-type axial staged MILD burner with geometrically induced enhanced internal circulation~~,~~ and ~~completed experiments~~performed trials under atmospheric pressure with ~~different~~various air injection schemes ~~under atmospheric pressure. The~~. OH* chemiluminescence revealed the pattern of MILD combustion ~~was observed by OH* chemiluminescence~~, and NO_x and CO emissions were measured to be below 8ppm and 25ppm, respectively.

According to the above research ~~work~~, it ~~can be seen~~is clear that the research on axial staged MILD combustion is mainly ~~focuses on~~concerned with the flow conditions and structural forms required to ~~achieve~~establish a mild environment within a confined load range under atmospheric pressure. ~~However, the~~The gas turbine, on the other hand, operates in a high-pressure environment, and the combustion chamber pressure and inlet flow ~~change~~alter with ~~the change of~~ load, which has a ~~great~~significant impact on MILD combustion by ~~affecting~~changing thermodynamics and chemical kinetics. ~~At present, there~~There is currently no ~~literature to study~~studies investigates the realization conditions of axial staged MILD combustion in ~~combination~~connection with ~~the~~ actual variable load characteristics of gas ~~turbines unit, especially considering the specific strategies.~~ turbine units. Therefore, ~~this paper takes~~taking the PG9351FA gas turbine as an example, ~~establishes~~this research develops a combined cycle variable working condition model~~,~~ and calculates the combustor parameters ~~of the combustion chamber~~ in the variable load process ~~under~~using two ~~adjustment~~control strategies. ~~Then~~The fuel and air distribution in the variable load is then studied using an axial staged MILD combustion CRN model~~ is established to study the fuel and air distribution of MILD combustion in the variable load.~~. In our previous work, the fuel and air distribution ~~have been shown~~were proven to be ~~an important factor~~critical factors in ~~realizing~~achieving MILD combustion under atmospheric pressure experiments [9]. The current ~~study is further present to investigate~~research will also look into the ~~possibility~~possibilities of ~~achieving~~establishing MILD combustion in a ~~large load~~broad turndown range ~~using~~ in actual gas turbine operation employing axial staged MILD combustion technology~~ in real gas turbine operation. To achieve~~. A re-staged secondary stage approach is presented to enable MILD combustion from ~~0~~zero loads to baseload~~, a re-staged secondary stage method is proposed~~.

METHODOLOGIES

CONTROL STRATEGIES FOR GAS TURBINE UNITS

~~The combined cycle model of the gas turbine is not specified in this paper and the establishment of the model refers to the literature [14, 15]. There are many adjustment strategies for variable load units. This paper selects two common strategies including the inlet guide vane (IGV) strategy and the fuel-only strategy, as follows:~~

~~1. IGV strategy.~~ The inlet guide vane (IGV) approach and the fuel-only method are two control systems for variable load units. The IGV is a stationary blade with an adjustable angle that sits in front of the first-stage moving blade at the compressor's inlet. By adjusting the angle of the IGV, the input air flow m_a can be changed, allowing the air-fuel ratio to be controlled to satisfy the operational needs of gas turbine. The method of regulating inlet temperature T_3 and exhaust temperature T_4 is chosen for optimal efficiency [14]. The comparison of the two strategies is shown in Table 1 and the detailed processes are as follows:

The IGV is fully opened to generate the baseload. During the load reduction, the IGV angle is adjusted to ensure the ~~turbine inlet temperature T_3 is~~T_3 constant as the design operating condition while the ~~turbine exhaust temperature T_4~~ T_4 progressively increases. When the T_4 ~~increases to the~~reaches its maximum value, ~~ensure that the maximum value of T_4 remains consistent, and the IGV angle continues~~keep T_4 unchanged and continue to ~~be changed until the IGV is adjusted to the maximum. Then~~adjust the IGV angle until the maximum angle is ~~retained constant, and~~reached. The IGV angle is then fixed, leaving only the fuel m_f to ~~be adjusted as~~vary when the load ~~declines~~decreases [14]. ~~The IGV strategy is a common regulation method for~~For heavy-duty gas turbines, the IGV strategy is a typical regulating method [15, 16~~, 17~~].

~~2. Fuel-only strategy. The airflow remains constant, and only the fuel flow reduces during load reduction.~~

The fuel-only strategy means that only the fuel is reduced during load reduction, while the air flow remains constant. This strategy is mainly used on micro gas turbines and special heavy-duty gas turbines. In many burner studies, only fuel variation is considered, i.e., the fuel-only strategy. Therefore, the analysis of this strategy can be used as a comparison.

Table 1 A Summary of Various Control Strategies

Strategy	Operating requirements	
IGV	$m_a, m_f \downarrow$ $\rightarrow m_f \downarrow$	$T_3 = c, T_4 \uparrow \rightarrow T_4 = T_{4max}, T_3 \downarrow$ $\rightarrow T_3, T_4 \downarrow$
Fuel-only	$m_f \downarrow$	$T_3 \downarrow, T_4 \downarrow$

The combined cycle model of the gas turbine is not stated in this paper and the establishment of the model is based on the literature [14, 17].

CRN MODELING OF THE AXIAL ~~STAGE~~STAGED MILD COMBUSTION

Figure 2 shows a simplified axial staged MILD combustion model~~, directly constructing~~ established by CHEMKIN software, which constructs two sequential PSRs~~ to represent the reaction between the two stages, of which~~ , PSR1 ~~represents~~and PSR2, respectively, for the primary and secondary stage~~, and PSR2 represents the secondary stage. The~~. At baseload, the total residence time is set to 25ms~~ concerning~~, which is comparable to the typical residence time of gas turbines [7], and each stage is identical~~ at baseload.~~. The volumes of the reactors remain constant during the load reduction. This model differs from our previous model [9] by omitting the post-flame region of the PFR simulation as emission characteristics are no longer studied. When the mixture undergoes MILD combustion, the temperature field is ~~uniform~~homogeneous. Doan et al. [18] investigated the DNS data and ~~found~~revealed that ~~autoignition is~~ the main combustion mode of MILD combustion is autoignition. The mixture fraction characteristic scale is similar to the chemical scale, the mixture fraction stratification causes the ignition delayed time gradient, and the reaction kinetics limit the progress of MILD combustion. ~~These~~With these characteristics~~ indicate that~~, the PSR model is ~~suitable for~~well suited to simulating premixed MILD combustion. Huang et al. [12] also studied axial staged MILD combustion by establishing two-stage PSRs. The composition and temperature of the mixture enter the CHBR (Closed Homogeneous Batch Reactor). On the reactor temperature versus time curve, the corresponding time of the maximum slop is the ignition delay time τ. Only the composition of the mixture enters the CHBR~~,~~ and given

~~different~~varied reactor temperatures, on the maximum ~~rector~~reactor temperature versus ~~rector~~reactor temperature cure, the corresponding reactor temperature of the maximum slop is the autoignition temperature T_{si} of the mixture.

~~The flow rates of~~ m_{a1} and m_{f1} are the air and fuel ~~entering~~flow rates into the primary stage ~~are m_{a1} and m_{f1},~~, respectively. ~~The flow rates of air and fuel entering the second stage are~~ m_{a2} and m_{f2}~~,~~ are the air and fuel flow rates into the secondary stage, respectively. The airflow staged ratio (AR) and ~~the~~ fuel staged ratio (FR) are defined as follows,

$$AR = \cancel{\frac{m_{a1}}{m_{a2}+m_{a2}}}\frac{m_{a1}}{m_{a1}+m_{a2}};\ FR = \frac{m_{f1}}{m_{f1}+m_{f2}}$$

(1)

The temperature of the Mixer is T_{mix}, and the temperature rise ΔT is the difference between the outlet temperature of PSR2 and T_{mix}. Therefore, the MILD combustion is achieved when the temperature relationship satisfies the condition: $T_{mix} > T_{si}$, $\Delta T < T_{si}$~~, the MILD combustion is achieved.~~.

As we all know, the mixing time ~~is generally less than 1 ms~~ in ~~actually~~ staged combustion chambers is typically less than 1 ms [19]. ~~In this~~This study~~, τ is calculated by~~ calculates the ~~full~~perfect mixing of fuel-air and gas in the Mixer ~~under ideal conditions~~, which is the longest time to ~~ignition~~ignite. In fact, ~~due to the non-uniformity of mixing, the fuel is~~ as it is in a high~~-~~-temperature gas environment, ~~τ~~the fuel is usually shorter than this calculated~~. The time scale~~ because of the non-uniformity of mixing. In MILD combustion, the time scales of flow and chemical reaction are comparable ~~in MILD combustion,~~ , i.e., ~~from the perspective of chemical kinetics, it is considered that~~ the τ of ~~the~~ secondary stage mixture ~~needs to exceed~~must surpass 1ms~~. In order to ensure the combustion efficiency, it is also necessary to satisfy τ < 12.5ms, even~~ in terms of chemical kinetics. Even if the secondary residence time is ~~large enough~~sufficient, the maximum ~~τ~~ cannot exceed ~~25ms.~~12.5 ms in order to ensure combustion efficiency.

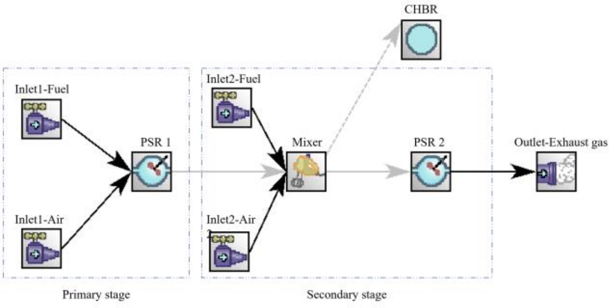


Figure 2. ~~Chemical Reaction Network~~CRN Model for Axial Staged MILD Combustion

RESULT AND DISCUSSION

PARAMETERS OF VARIABLE LOAD

VALIDATION

The traditional PG9351FA gas turbine is selected as the research object. When it is running at the baseload, the ~~pressure is 15.52 bar and the outlet temperature of the combustion chamber is 1394℃~~parameters is shown in Table 2 [20]. Figure 3 shows the comparison between the simulation results and the literature [14]. It can be seen that the simulation results in this ~~paper~~study are consistent with the data given in the literature~~. Within the error range,~~, and the calculation results of variable load parameters are considered reliable.

Table 2 The Operation Parameters in Baseload

Parameters	Value	Parameters	Value
The flow of air	529.52 kg/s	Fuel	Methane
The flow of fuel	14.84 kg/s	Outlet temperature	1394 °C
Pressure	15.52 bar		

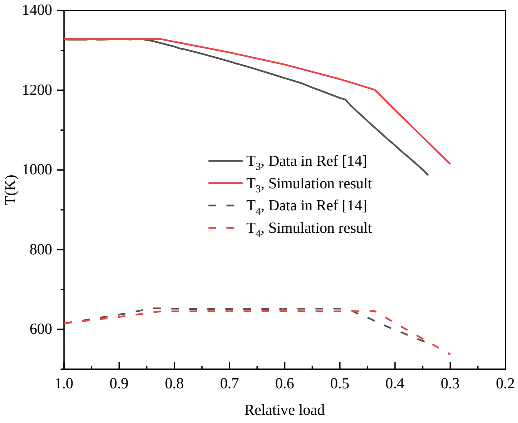


Figure 3 Comparison of the Results with the Ref [14]

PARAMETERS

The operating parameters of the combustion chamber under partial load are shown in Figure 4. In the IGV strategy, the T_4 ~~reaches~~is fixed a maximum and the IGV angle is adjusted to the maximum when the gas turbine load is reduced to 77.4% and 34.94%, respectively. Since then, as the load decreases, the trend of IGV strategy parameters is the same as that of the fuel-only strategy.

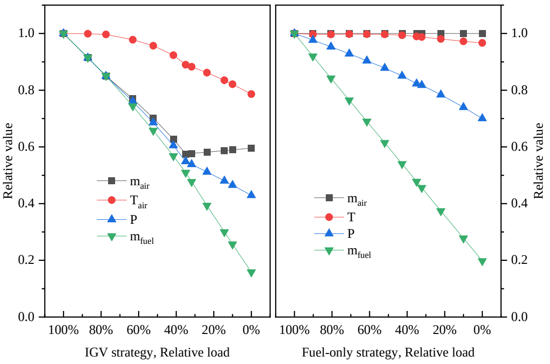


Figure 4 The Parameters of the Combustor in Variable Load

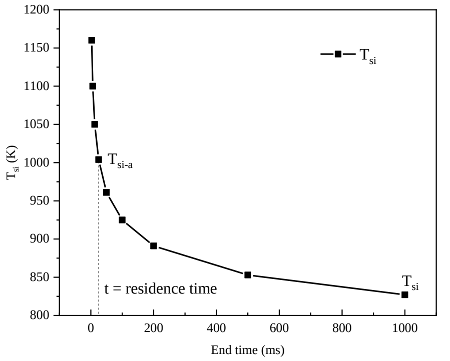
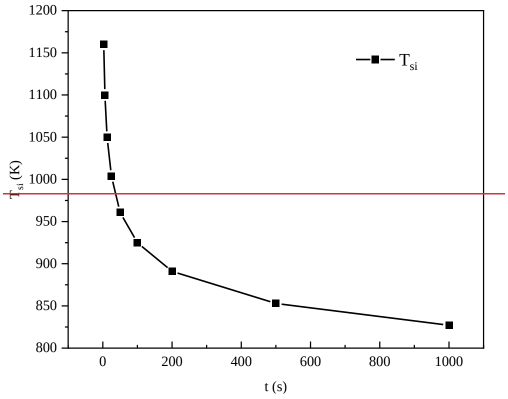


Figure 5 The Effect of End Time on T_{si}

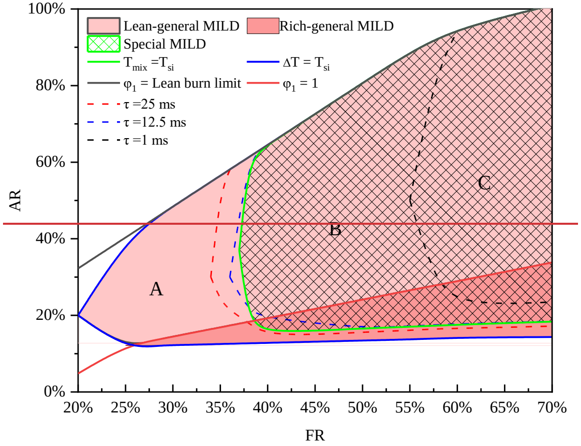
PARAMETERS ANALYSIS

During the ~~Chemkin~~CHEMKIN calculation, the GRI3.0 mechanism file is selected [21]~~.~~ as methane is selected as the fuel. When calculating the τ and T_{si}, the end time of CHBR is a crucial parameter and is usually set to 1s [5]. ~~It is obvious that the τ is not related to the end time, and only needs to ensure the end time is greater than the τ.~~ Fixed AR=FR=50% and set a range of different end times, the effect of ~~the~~ end time on T_{si} is shown in Figure 5. As the end time increases, the –T_{si} decreases significantly. ~~Therefore, it~~It is necessary to think deeply about the definition of MILD combustion considering the effect of T_{si}. As ~~we~~well all know, MILD combustion is initially ~~used~~utilized in the furnace and the mixture's residence time inside the furnace is long enough that the end time set to 1s is reasonable. ~~The T_{si}~~In the combustion chamber, the residence time of the mixture is particularly small, and the autoignition temperature calculated ~~with a sufficiently long time (1s) and the~~ from actual gas turbine residence time ~~are~~is T_{si-a} . The difference between T_{si} and T_{si-a} ~~, respectively~~ is shown in Figure5, ant the former is much smaller than the latter. Here, the MILD combustion determined with the T_{si} is defined as general MILD combustion, while determined with the T_{si-a} is defined as special MILD combustion.



EFFECT OF STAGE RATIO ON BASELOAD

The effects of FR and AR on the combustion state at the baseload are shown in Figure 6. The AR and FR in the red region form ~~general~~ MILD combustion. It can be seen that ~~when the FR is greater than 20%,~~ there is a general MILD combustion region~~.~~ when the FR is greater than 20%. The minimum value of AR is limited by ΔT and T_{si}, and their relationship can also limit the maximum value of AR at smaller FR. When the FR is larger, fixed the FR, as the AR increases, the amount of primary air increases, resulting in a gradual decrease in the primary equivalence ratio. The AR continues to increase until the primary stage cannot burn (φ_1 represents the primary equivalence ratio), at which point the maximum value of AR is determined by the ~~primary~~ lean burn limit~~.~~ of primary stage. Compared to the general MILD combustion, the ~~AR and FR in the shaded~~ region ~~form~~of special MILD is relatively narrower. As mentioned in Figure 5, T_{si-a} is larger than T_{si} by near 200 K, and ΔT is always smaller than the T_{si-a}. The limit of MILD combustion~~. Regarding~~ range is the relationship between T_{mix} and T_{si-a}. At the same time, for the special MILD combustion, the ~~FR is greater than 37%, and the~~ minimum value of ~~AR is limited by T_{mix} and T_{si-a}.~~FR is 37%.



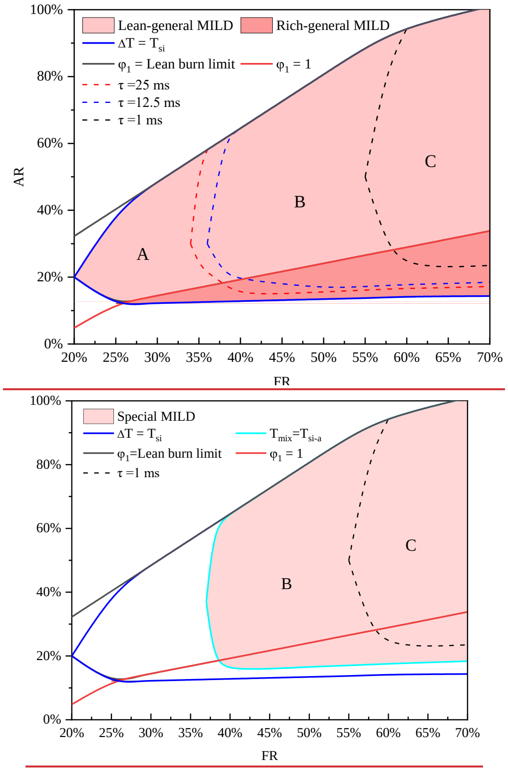
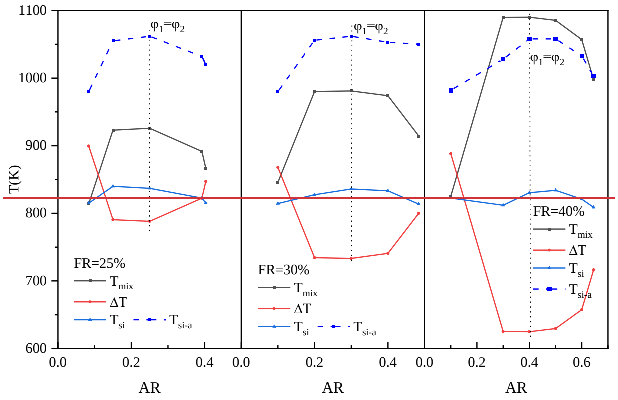


Figure 6 The Effect of FR and AR on MILD Combustion



~~Figure 7 The Effect of AR on T~~

Figure 7 shows the relationship between temperature and AR at FR = 25%, 30%, and 40%, respectively. The maximum value of AR corresponds to the lean burn limit in Figure 6. When the AR is large, the T_{mix} is much greater than T_{si}, and the ΔT is smaller than the T_{si}. As the FR decreases, ΔT gradually increases (e.g., FR=25%, $\Delta T > T_{si}$), and the critical value of FR is 28.8%. Therefore, the maximum AR is determined by the lean combustion limit at FR>28.8%, and the maximum AR is determined by the relationship between ΔT and T_{si} at FR<28.8%. When the AR is relatively small, the curves of ΔT, T_{mix} and T_{si} intersect. The AR corresponding to the intersection of ΔT and T_{si} is larger, which determines the minimum AR of general MILD combustion. With the reduction of FR, the AR range of MILD combustion gradually decreases. When FR=20%, the ΔT coincides with the two intersections of T_{si}, i.e., general MILD combustion cannot be achieved at FR<20%. Nevertheless, the T_{si-a} is much larger than T_{si}, and it is only when FR is particularly large that T_{mix} can intersect with T_{si-a}(e.g., FR=40%).

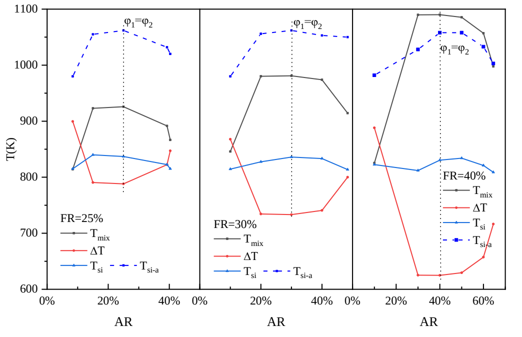


Figure 7 The Effect of AR on T

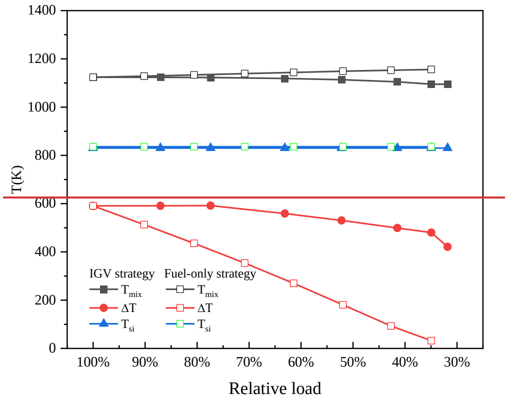
According to the primary stage equivalence ratio, the AR range of Figure 6 is divided, and it is found that the area that can achieve lean-general MILD combustion is much larger than that of rich-general MILD combustion. Lean-general MILD combustion can make full use of the low NO_x advantage of the existing lean premixed combustion technology and is more suitable for design baseload. The dotted lines in Figure 6 represent τ=1ms, 12.5ms and 25ms, respectively. It can be seen that the smaller the FR, the larger the τ. When the FR is less than 36%, the entire general MILD burning range of τ is greater than 12.5ms. Especially when the FR is less than 34%, τ is greater than 25ms, i.e., the area A in the figure, the secondary combustion efficiency needs to be paid attention to. In area C, τ<1ms, even if the MILD combustion is satisfied, the τ is too short to organize the flow. Hence, in terms of chemical kinetic, the optimal for achieving MILD combustion is region B (The area is bounded by τ=1ms and τ=12.5ms).

It should be emphasized that the curve τ=12.5ms almost coincides with the special MILD combustion boundary $T_{mix} = T_{si-a}$ as the end time is set to 12.5ms when calculating the T_{si-a} in CHBR. The mixture must stay in the CHBR longer than the τ before the combustion reaction can occur. If the end time is set to a larger value of 25ms, the border of special MILD combustion will move closer to the right of τ=25ms. That is, special MILD combustion is almost essentially the same as general MILD combustion controlled by the τ. Regardless of whether it is reflected in the τ or the T_{si-a}, in actual gas turbine, the influence of chemical kinetic factors on MILD combustion is still very large and must be considered. For convenience, the following text no longer emphasizes the difference between general and special and only uses MILD combustion to represent this technology.

In addition, the dotted line in Figure 7 indicates that the two stage equivalence ratios are the same and equal to the global equivalence ratio. At this condition, the T_{mix} is the largest and the ΔT is the smallest, which is most in line with the temperature relationship of MILD combustion. In summary, for the PG9351FA unit to achieve axial staged MILD combustion, the primary fuel distribution ratio is not less than 20% at baseload, and the higher primary the fuel distribution ratio, the wider range of staging ratio. Taking into account the τ, the fuel air flow distribution needs to be in area B in Figure 6. To achieve lean-MILD combustion, the FR range is 37% < FR<60% and it is the best staged ratio when the equivalences of the two stages are the same.

EFFECT OF ~~DIFFERENT~~ STRATEGIES ON VARIABLE LOAD

The distribution ratio of air flow between stages is determined by the structure of the combustion chamber and does not change. ~~Fixed the~~Figure 8 compares the two control procedures when τ~~=5ms~~ = 5 ms at baseload [22] and ~~fixed~~ the primary stage equivalence ratio φ_1 is fixed during the load reduction process~~, the comparison under the two control strategies is shown in Figure 8~~. With the load decreasing, both strategies can always maintain MILD combustion. The T_{mix} and the ΔT remain unchanged until the load reduces to 77.4%, then both gradually decrease with load reduction in IGV strategy. When the load is reduced to the maximum of IGV ~~adjustment~~angle, T_{mix} is almost unchanged while ΔT decreases linearly. In contrast, with the decrease of load, the change of T_{mix} and ΔT in fuel-only strategy is the same as that of IGV strategy after maximum regulation. Due to the air temperature is lower in IGV strategy, resulting in the T_{mix} is lower than that of the fuel-only strategy at the same load, and the ΔT is the opposite. Compared to the two strategies, the differences in T_{mix} and ΔT gradually increase with the decrease of load. The effect of this difference is particularly pronounced on the τ.



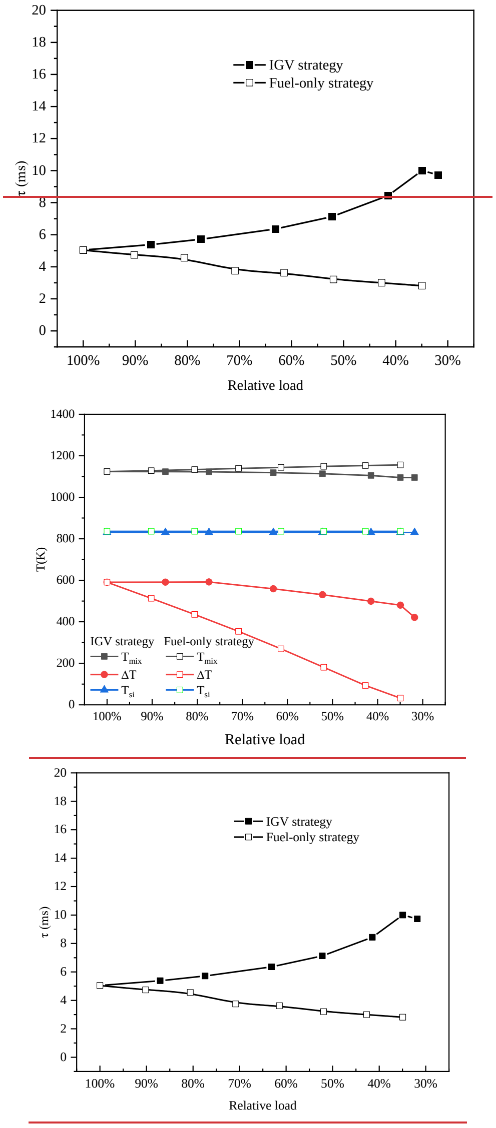


Figure 8 Comparison of Two Control Strategies

The τ increases in IGV strategy while decreases in the fuel-only strategy with the load decreasing. As the τ is related to the pressure, temperature and concentration of reactants, the influence of each parameter on the τ is shown in Figure 9. It can be seen that the τ increases as the pressure and temperature decrease, but decreases as the relative flow of air and fuel decreases. The coupling effect of all parameters results in ~~the increase~~an opposite trend under the ~~IGV strategy and the decrease under the fuel-only strategy~~two strategies in Figure 8. ~~This shows that in the~~In IGV strategy, the decrease in air temperature causes the drop in T_{mix} that plays a major role in τ. Nevertheless, in~~ the~~ fuel-only strategy, the air temperature change is relatively small that the decrease in the secondary fuel flow is stronger. Comparing the changes of τ, it is found that the IGV strategy has a larger range, while under the fuel-only strategy, the τ decreases more slowly and the relative change in τ is lower than 45%. The change of τ in the process of variable load is as small as possible, which could avoid exceeding the limits.

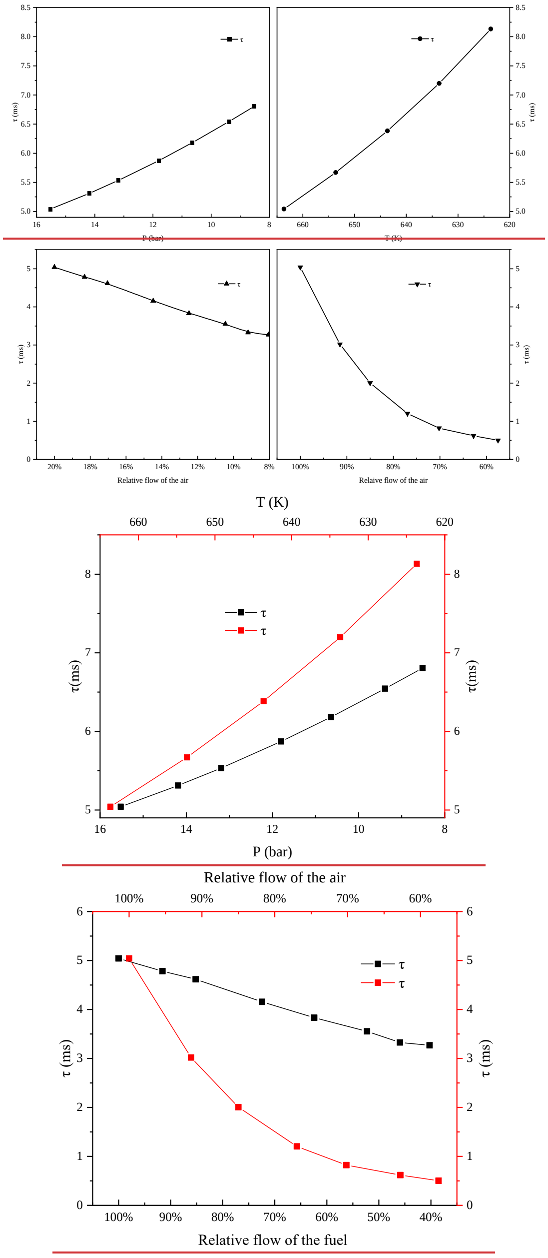


Figure 9 The Effect of Variable Parameters on τ

Since the T_{mix} is the main reason causing the τ increasing, controlling the change in T_{mix} is the best way. As shown in Figure 10, where T₁ represents the outlet gas temperature of primary stage. The temperature of T₁ cannot be increased during the load reductions to avoid overheating and bringing problems to the cooling of the combustion chamber. Compared to the fixed in φ_1, fixing in T₁ attenuates the drop in T_{mix} so that the τ changes more slowly. Since the air temperature gradually decreases as the load drops, the φ_1 needs to be slightly increased to keep the T₁ constant.

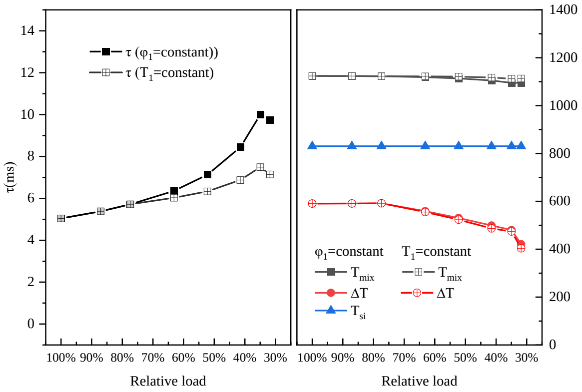
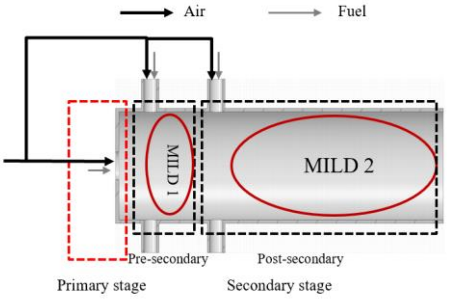


Figure 10 T₁ Regulation in IGV Strategy

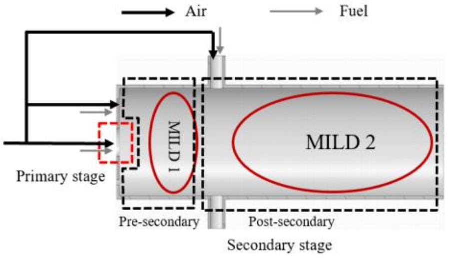
Therefore, MILD combustion can ~~always~~ be maintained ~~in thermodynamical during load drops process, and~~for both strategies ~~can satisfy the limitation of the τ. The minimum value of the load variation range of MILD combustion is determined by reducing~~under variable load process before the secondary stage fuel is reduced to ~~0. Theoretically, the primary stage forms premixed combustion and the~~zero. For fuel-only strategy, keeping φ_1 unchanged is sufficient, while for IGV strategy, it is better to keep T₁ unchanged. Since the F-class or higher-class gas ~~entering the second stage is only air acting as cooling air below this load.~~ turbines are mainly control by IGV strategy, fixing T₁ is the most preferred way instead of the commonly way of fixing φ_1 when studying various loads.

As shown in Figure 4, whether in the IGV strategy or the fuel-only strategy, the fuel flow rate is less than 20% at zero load. ~~Combining~~Considering that only the primary stage is running when the unit starts to zero load, combined with Figure 6, it ~~can~~will be ~~seen that if this amount of fuel is used as the primary fuel, it will~~found that not only fail to build MILD combustion, but also lead to a particularly large ignition delay time. Therefore, it is considered to divide the secondary stage and discuss the re-staged behaviour to realize MILD combustion from ~~0 loads~~zero load to baseload.

The secondary stage is divided into two stages, called the pre-secondary stage and the post-secondary stage, respectively. It is emphasized that the form of re-staged is not limited to the axial (Figure 11a), but can also be radial (Figure 11b) or other forms. The purpose of re-staged is to mix the gas of the primary stage with the pre-secondary stage to achieve MILD combustion in pre-secondary stage, which benefits are more obvious at low loads. At higher loads~~ after a certain load~~, the gas of the primary stage and the pre-secondary stage are used together to realize the MILD combustion of the post-~~second~~secondary stage. The primary stage and the pre-secondary stage are taken together to be essentially the same as the primary stage especially in baseload. In order to maintain the concept of MILD combustion in secondary stage, the mentioned re-staged is named. As above, at baseload, the sum of the fuel distribution of the primary and pre-secondary stages is required to satisfy the condition 37%<FR<60%.



a Axial Re-staged



b Radial Re-staged

Figure 11 The Form of Re-staged in Secondary Stage

The air distribution of the primary stage and the pre-secondary stage is also determined by the combustion chamber structure and remains constant at varying loads. For the above fixed τ=5ms at baseload, the variable load process combined with the primary and the pre-secondary stages should comply with Figure 8. At low loads after the IGV angle is ~~adjusted to maximum~~fixed, the IGV strategy is the same as the fuel-only strategy. Therefore, during the entire variable load process from baseload to ~~0~~zero load, the fuel flow of each stage is shown in Figure 12.

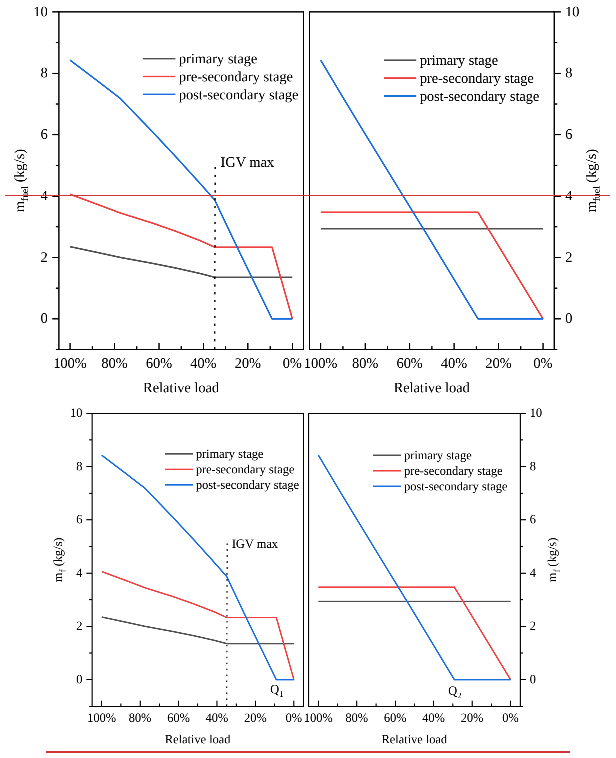


Figure 12 The Flow of Fuel During Variable Load

The comparison of whether to re-stage to achieve MILD combustion is shown in Table 3, where Q_1 and Q_2 can be obtained from Figure 12. Through the form of re-stage, both strategies can achieve MILD combustion from zero load to baseload. It is ~~believe~~believed that in addition to the other strategies~~ studied in this paper~~, MILD combustion~~ from 0 loads to full load~~ can be achieved by staging the secondary stage. The difference is that the fuel and air distribution ratio of variable load ~~is different under different~~ varies depending on the strategies. In other words, the ~~load~~turndown ranges to sequentially adjust the post-secondary stage, the pre-secondary stage, and the primary stage are distinct.

Table 3 Comparison of the Re-stage

Re-stage	Strategies	Start running secondary stage	MILD range	Reason
No	Both	0 load	No	$\Delta T > T_{si}$; τ too large
	IGV	Q_1 load	100%-9.2%	m_{f2}_ decreases to 0
	Fuel-only	Q_2 load	100%-29.2%	
Yes	Both	0 load	100%-0	

CONCLUSIONS

~~This paper takes PG9351FA as an example to calculate the~~ The variable load operating ~~parameters~~ characteristics of the combustion chamber in IGV ~~strategy~~ and fuel-only ~~strategy. Combined with~~strategies are calculated using PG9351FA as an example. The distribution of fuel and air flow in a variable load process is investigated using the established CRN model of axial staged MILD combustion~~, the distribution of the flow of fuel and air in the process of variable load is studied. To achieve~~. A re-staged method is proposed to enable MILD combustion from ~~0 loads~~zero load to baseload~~, a method of re-staged is proposed. The~~ . The following are the main conclusions~~ are as follows~~:

1. The T_{si-a} calculated ~~by considering~~using the actual residence time is higher than the T_{si} calculated using the convention~~ T_{si} .~~. The T_{si-a} and the τ ~~are similar to constrain~~constraint on MILD combustion~~. Therefore~~ are similar. As a result, when developing MILD combustion, both thermodynamics and kinetics ~~need to~~must be ~~considered when designing MILD combustion.~~taken into account.

2. The AF and FR are ~~important factors and~~key parameters that should be ~~limited~~kept within a certain range, where FR should be larger than 20%, but the chemical kinetics requires 37%<FR<60% at baseload. ~~It is the best staged ratio when~~When the equivalences of the stages are the same, it is the best staged ratio.

3. In the process of variable load, keeping the primary stage equivalence ratio constant, MILD combustion can be maintained all the time. Under the IGV strategy, it is more advantageous to keep the temperature of the primary stage gas unchanged.

~~3~~4. By re-~~staged~~staging the secondary stage, the secondary stage of axial staged can realize MILD combustion from baseload to ~~0~~zero load.

This work is to provide a guidance for first cut design of a MILD combustor by mean of axial staged. In the future, a full CRN model analysis of the complex flow and reaction in a given burner will be undertaken to better demonstrate the feasibility of the technology.

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