Study on the Influence of Premix Uniformity on NOx Emission Concentration in 9E Gas Turbine Combustion Chamber

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Abstract. In this paper, a numerical simulation is performed on the basis of a combustion chamber of 9E gas turbine, to study the effect of premix uniformity on the NOx emission concentration. The results show that when the 9E gas turbine is working under the baseload with a fuel flow ratio of the primary nozzle \( R_{\text{fuel}} \) deviates within an optimal interval of 78 % to 84 %, an increment in the number of secondary nozzle fuel injection points leads to a decline in NOx emission concentration. Since purge air nozzles of DLN are placed in upstream of swirl generator while the nozzles are placed downstream of swirl generator in LEC, the impact of the purge airflow rate on the NOx emission in the DLN has an opposite trend with that in the LEC. Besides, the increment of the mixed air proportion \( R_{\text{air}} \) leads to a distinct enhancement in the local equivalence ratio peak value of the primary combustion zone outlet. Also, the distribution of the equivalence ratio changes. The NOx emission concentration is influenced as a result.

1. Introduction

For the purpose of controlling NOx emission, dry low nitrogen combustion technology is widely applied in modern gas turbine engines. The 9E gas turbine has been utilized as an advanced combustion system named DLN1.0, which shifts the combustion mode according to the stage of load during the period from self-triggering to full load. When the gas turbine is working under the baseload with the premix combustion mode, the DLN1.0 system ensures a lower combustion temperature, a stable combustion status, and a low NOx emission concentration as a result.[1-2]

After being put into application, the DLN1.0 system was updated and named DLN1.0+[3]. The GE company optimized the primary nozzles, venturi section, and pilot fuel line, so that the local flame temperature was reduced, and thus the NOx emission was suppressed. Moreover, optimizations were conducted to several connectors to pursue a better stress distribution, therefore a longer life-span. In reference [4], the actual performance of the DLN1.0+ was reported, and it was proved that a NOx emission concentration below 10 mg/m^3 was acquired by the DLN1.0+.

PSM company also developed an advanced system on the basis of the 9E gas turbine, which was name LEC-III. The LEC-III system had the same geometric demission as that of the DLN1.0 system, which meat that the LEC-III was an alternative to the DLN. However, the secondary nozzle and the venturi section in the LEC-III were optimized on the basis of the DLN. As a result, the fuel injection had a more uniform circumferential distribution, and the cooling air backflow was prevented. The above optimizations led to an obvious reduction in both the NOx and CO emission. After that, the secondary nozzles were further optimized and the LEC-NextGen was developed[5]. The fuel radial distribution was improved, the temperature of the local hot point was further decreased, and NOx emission concentration declined to a level below10 mg/m^3[6].
In this paper, a numerical simulation is conducted to study the combustion status of DLN1.0 and LEC-NextGen. By comparing the results, the method of designing a system with lower NOx emission is revealed.

2. Simplified geometric model of 9E combustion chamber and boundary conditions

Figure 1(a) depicts the simplified geometric model of the combustion chamber, and Figure 2(b) reveals the grids of the computational zone. The boundary conditions of the baseload are the same as those in reference[7]. The gas turbine baseload is 123.4MW, the mass flow rate at the gas turbine inlet is 403.7kg/s, the pressure ratio is 12.3, airflow rate at the inlet of the combustion chamber is 83% of that at the inlet of the compressor. According to the hole area of the combustion chamber reported in reference[8].

3. Numerical method and validations

The commercial software Fluent is applied to solve the basic equations that describe the turbulent combustion process. The equations are listed below:

\[ \frac{\partial \rho}{\partial t} + \frac{\partial \rho u_i}{\partial x_i} = 0 \]  
(1)

\[ \frac{\partial \rho u_i}{\partial t} + \frac{\partial \rho u_i u_j}{\partial x_j} = -\frac{\partial \rho}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} \]  
(2)

\[ \frac{\partial \rho h}{\partial t} + \frac{\partial \rho h u_j}{\partial x_j} = \frac{\partial p}{\partial t} + \frac{\partial}{\partial x_j} \left( \frac{\mu}{Pr} \frac{\partial h}{\partial x_j} \right) + \omega_t \]  
(3)
\[ \frac{\partial \rho Y_i}{\partial t} + \frac{\partial \rho u_i Y_i}{\partial x_j} = \frac{\partial}{\partial x_j} \left( \frac{\mu}{Sc} \frac{\partial Y_i}{\partial x_j} \right) + \omega_i \]  

(4)

in which, \( \rho \), \( u_i \), \( p \), \( \tau_{ij} \), \( h \), \( \omega_t \), and \( \omega_i \) refers to density, velocity, pressure, viscous stress, total enthalpy, heat-releasing rate, and reaction rate of component \( i \) respectively.

The realizable \( k-\varepsilon \) turbulence model is applied in the present study[9], the Finite-rate/Eddy Dissipation is applied to the combustion mode, and the combustion process of methane is simulated by the two-step reaction.

4. The effect of injection method of the secondary nozzle

There are four combustion modes of the 9E gas turbine, which can be chosen according to different stages of the operating load. In the present study, the simulation is conducted on the basis of the premix combustion mode with the baseline. Under the premixing mode, the ratio of the fuel flow rate in primary combustion zone to the total fuel flow rate, which is named \( R_{\text{fuel}} \) in this paper, is 80%. However, the value of \( R_{\text{fuel}} \) is adjusted according to factors such as ambient temperature and natural gas heat value, so that a low level of NOx emission is ensured. Based on operation experiences of the 9E system, the lowest NOx emission concentration is acquired when the \( R_{\text{fuel}} \) ranges from 80% to 82%.

Figure. 3 illustrates the effect of \( R_{\text{fuel}} \) on the NOx emission concentration. Both the DLN1.0 and the LEC-NexGen are taken into consideration. It can be inferred that, the curve of the NOx emission concentration versus the \( R_{\text{fuel}} \) is bowl-shaped. When the \( R_{\text{fuel}} \) varies within an optimal interval of 78%~84%, the NOx emission concentration for the LEC is apparently lower than that of the DLN. Particularly when \( R_{\text{fuel}} \) is 82%, the lowest NOx emission concentration of LEC appears, which is only 75% of that of the DLN.

![Figure 3](image-url)

Figure 3. The effect of \( R_{\text{fuel}} \) on the NOx emission concentration.

Figure 4 illustrates the temperature distribution in the middle section of DLN and LEC respectively. When \( R_{\text{fuel}} \) is 76%, the equivalence ratio at the secondary combustion zone outlet is 0.93. LEC shows little improvement in NOx emission and chamber center temperature. This is because as the fuel flow of the primary combustion zone decreases, the fuel flow rate of the secondary combustion zone increases dramatically. As a result, the equivalence ratio at the outlet of the secondary combustion zone is enhanced.

As \( R_{\text{fuel}} \) further increases, the center combustion zone temperature and NOx emission concentration of the DLN and LEC are both decreased. This is because as the fuel flow rate of the secondary combustion zone declines dramatically as the fuel flow rate of the primary combustion zone increases. Thus, the flame temperature is lower, and combustion at the outside edge of the combustor contributes mostly to the NOx emission. As the local equivalence ratio at the outside edge of the LEC secondary nozzle outlet is obviously higher than that of DLN, more fuel is entrained by swirl generated by swirl generator of the secondary combustion zone. This part of the fuel is left and burnt around the outside edge of the
secondary combustion zone. As a result, the outer side NOx emission concentration of the LEC is a little higher than that of the DLN, as is shown in Figure 5.

\[
\text{Temperature (K)}
\]

(a) \( R_{\text{fuel}}=76\% \quad (b) \ R_{\text{fuel}}=82\% \quad (c) \ R_{\text{fuel}}=86\%
\]

Figure 4 Temperature distribution in the middle section of DLN and LEC respectively, \( R_{\text{fuel}}=76\%, 82\%, 86\% \).

\[
\text{NOx mass fraction}
\]

(a) \( R_{\text{fuel}}=76\% \quad (b) \ R_{\text{fuel}}=82\% \quad (c) \ R_{\text{fuel}}=86\%
\]

Figure 5 NOx emission concentration distribution in the middle section of DLN and LEC, \( R_{\text{fuel}}=76\%, 82\%, 86\% \).

5. Effect of purge air

In this section, a dimensionless flow rate \( M_{\text{purge}} \) is adopted to evaluate the flow rate of the purge air. \( M_{\text{purge}} \) is defined as the ratio of actual flow rate to designed flow rate. In Figure 6, the effect of injection location of purge air and \( M_{\text{purge}} \) on the NOx emission concentration is plotted. Since purge air nozzles of DLN are placed in upstream of swirl generator while the nozzles are placed downstream of swirl generator in LEC, the curve of the DLN has an opposite trend with that of the LEC. As \( M_{\text{purge}} \) increases from 0.5 to 2.5, the NOx emission concentration of the DLN dramatically drops from around 28 mg/m\(^3\) to 7.8 mg/m\(^3\). However, the NOx emission concentration of the LEC experiences a stable period as \( M_{\text{purge}} \) rises from 0.5 to 1.5; however, it doubles as the value of \( M_{\text{purge}} \) reaches 5.

\[
\begin{align*}
\text{NOx emission (mg/m}^3\text{)} \\
0 & \quad 5 & \quad 10 & \quad 15 & \quad 20 & \quad 25 & \quad 30 \\
\text{\( M_{\text{purge}} \) (m/s)}
\end{align*}
\]

Figure 6 Effect of purge air location and \( M_{\text{purge}} \) on the NOx emission concentration.

Figure 7 shows the local equivalence ratio of purge air contour in the middle section of DLN and LEC respectively, when \( M_{\text{purge}}=1.0, 2.5 \). As \( M_{\text{purge}} \) increases from 1.0 to 2.5, the high equivalence ratio area of DLN moves laterally. Since the purge air nozzles are placed in the upstream of swirl generator, the injected air, which has not been mixed with fuel, helps to form a low equivalence ratio zone that separates the premixing zone with the combustion zone. After the purge air passes through the swirl generator, the high equivalence ratio area moves laterally and the local equivalence ratio in the combustion area is decreased correspondingly.
While the purge air nozzles of LEC are placed in downstream of the swirl generator, and the local high equivalence ratio area moves inward as $M_{\text{purge}}$ increases. This is because the increment in $M_{\text{purge}}$ results in a stronger recirculation of purge air near the wall in front of nozzles. The strong circulation entrains the premix gas with a high equivalence ratio from the inner zone of the chamber, and thus the fuel concentration of the combustion chamber center area is enhanced.

### Figure 7

Local equivalence ratio of purge air contour in the middle section of DLN and LEC $M_{\text{purge}}=1.0, 2.5$.

(a) DLN

(b) LEC

### 6. Effect of mixing jet in the primary combustion zone

In this paper, the ratio of mixing jet flow rate to the total airflow rate in the primary zone is adopted as an important factor, which is defined as $R_{\text{air}}$. Figure 8 illustrates the effect of $R_{\text{air}}$ on the NOx emission concentration, with a constant primary combustion zone total airflow rate. The location of the mixing jet of the primary combustion zone is marked in Figure 1(a). The plot indicates that, either for DLN or LEC, the NOx emission concentration rises as the $R_{\text{air}}$ enhances. Besides, the slope of the curves also expands with the increment of $R_{\text{air}}$.

### Figure 8

Effect of $R_{\text{air}}$ on the NOx emission concentration.

Figure 9 depicts the local equivalence ratio distribution in the middle section of DLN when $R_{\text{air}}=38\%, 54\%$. Compare the local equivalence ratio cross-section contour of $R_{\text{air}}=38\%$ case to that of $R_{\text{air}}=54\%$ case, it’s apparent that the high equivalence ratio area moves outward as $R_{\text{air}}$ increases, and more fuel is pushed outward. When the $R_{\text{air}}$ is too high, the injection rushes straightly into the primary combustion zone without being fully mixed with the horizontal flow. The fuel that is not being mixed into injection is pushed outward and ultimately results in an enhancement in the equivalence ratio of the outer area. As a consequence, the premix uniformity is worsened. The increment in $R_{\text{air}}$ also affects the temperature distribution of the venturi tube outside the combustion zone. As a consequence, for both DLN and LEC, the NOx emission concentration is dramatically enhanced.
7. Conclusion
The research results of this paper show that: the injection mode of secondary nozzle fuel, the injection mode and relative flow rate of purge air, the proportion of mixing air flow rate in the primary combustion zone can all have a great impact on NOx emission concentration by changing the premix uniformity. For designers, they can flexibly use a variety of design schemes to change premix uniformity.

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