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Effects of scaling laws on flow and combustion characteristics of lean premixed swirl burners

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Abstract

Modern heavy gas turbine combustors are always huge, so it is difficult and costly to do experiment. Thus, geometry scaling method has come into sight. In this paper, based on a single lean premixed swirl burner, validated computational fluid dynamic (CFD) model was used to study the effects of different scaling laws on various scalling models from 1/2 to 1/10. Experimental study on prototype combustor and the 3/5 scale model under full operating condition is also carried out to verify the NOx emission under different laws. Results showed that Dal scaling law was able to maintain good similarity under combustion state when scaling factor = 1/2-1/5, while Re scaling law would bring significant changes on flow and flame characteristics. The emission of NOx is also similar to prototype by using Dai law. But Re law could keep flow characteristics under non-combustion state. It is suggested that Dai law is suitable for lean premixed swirl combustor geometry scaling.

Introduction

Recently, strict regulations on stationary power and heat production has facilitated the development of ultra low emission technologies. Dry low emission (DLE) combustion of Gas turbine has become the state of art. But DLE also brings problems such as combustion instabilities, flash back. Thus, DLE burners have to be design precisely in order to deal with new issues (Meraner et al., 2020). However, things won't be easy when designing industrial DLE burners like gas turbine combustors because of their huge size and large capacity. Experimental cost will be unacceptable. Under such circumstances, studies on scale-down models (Original ones are called as "prototype")-has come into sight. Then experiments can be carried out easier, which reduces the test requirements and costs.

Nevertheless, relations between model and prototype have to be determined firstly. Scaling laws have to be highly taken into consideration in order to formulate the test conditions of model considering the degree of scaling, which is similar to prototype. But according to similarity theory, the strict requirements of holding all criterions after scaling are shown to be so restrictive that complete modeling of combustion processes is practically impossible. In this case, Spalding et al. (1963) and Beér and Chigier (1972) indicated that keeping all criterions is unnecessary. That is because some influences are much weaker than others. Researchers should consider the most important one and negelect the others. This is called as "partial modeling". By this concept, researchers put forward different scaling laws. Although various scaling laws can be found in recent literatures, but most of them aimed at non-swirler jet flames, which provide a simple flow field (Popp et al., 2004). For industrial swirling burners, relevant studies are rare, much less gas turbine combustor. Weber reported two most frequently used laws - the constant velocity and the constant residence time principles. On these two laws, the IFRF in cooperation with the Gas Research Institute carried out the Study on furnaces (Weber, 1996; Hsieh et al., 1998; Weber and Breussin, 1998; Cheng et al., 2000; Szego et al., 2008; Barroso et al., 2020). But researchers did not prove which scaling law being superior over the the other and whether the two laws maintained flow and flame features. What's more, these two pricinples are essentially empirical and not match the basic critierions proposed by Damköhler (1937). Smart and Kamp (1999) found that neither of the laws were able to preserve flame structures and thermochemical fields when scaling a pulverised coal burner. So further study on industrial swirling combusiton scaling is needed.

When going back to basic theories, literatures can be found. Spalding had concluded the complete similarity criterion which can reflect the combustion process (Spalding et al., 1963). He listed some tables of similarity criteria applicable to the modeling of burners. Beér and Chigier (1972) indicated that for such process, Re and Da_I should be considered and the others should be neglected. Re is defined as formula 1:

$$Re = \frac{\rho v D}{\mu} \tag{1}$$

And Da_I is defined as formula 2:

$$Da_I = \frac{W_R D}{\rho Y_f v} \tag{2}$$

While Y_f stands for the mass fraction of the mixture and W_R stands for the reaction rate. When comparing the two above laws, we can find that if dimension changes, it is hard to keep Re and Da constant meanwhile. Thus, it is necessary to make a comparative analysis to find which one matters more. But relevant studies are so few to find.

Above all, although geometry scaling is so valuable, but "the scaling issue disappeared from the research agenda" in recent 20 years (Weber and Mancini, 2020). Many questions were left unanswered, like the scaling laws, relevance between model and prototype and size effect. To deal with this, the first step is to aquire the basic rule of DLE. Based on a lean premixed swirling combustor, this work presents first the scaling effects based on a set of 8 computational fluid dynamic (CFD) simulations at different scales from 1/2 to 1/10 and compared Re criterion and Da_I criterion. Then a series of experiments are carried out to validate the conclusion and acquire the scale effect on NOx emissions.

Methodology

Burner design

The burner employs a single swirl premixed combustor with a straight blade axial swirler. It reserves the basic properities of DLE burner. In numerical study, the geometric model is the similarity of the one in experiment. The structure and size parameters are shown in Figure 1. D represents the maximum outer diameter of the burner. For cases in numerical study, the scaling factor is 1, 1/2, 1/3, 1/4, 1/5 and 1/10. The combustion section is a $3D \times 3D$ square rectangular chamber. Four characteristic positions of interest in numerical simulation are also given in the figure. The blade angle of the axial swirler is 40.5 degree and the swirl number is 0.67, which generates swirl with medium intensity.

Numerical methods

The numerical model that was used for the simulations of the burner has been developed and validated in some previous works. For the axial swirler, Grech (Koupper et al., 2012) found that the error between simulation results and experiment is less than 2%, so the Realizable model is used to close the turbulent viscous stress term, and its governing equations can be referred to literature. The FGM premixed model is used to simulate the chemical reaction and validated by Zhang et al. (2020). Its governing equations can be referred to literature. The thermal boundary conditions for the lateral surfaces were modelled adiabatic. Based on these studies, a tendency to predict flow regime and flame structure can be expected.



Figure 1. Geometry parameters of the burner.

The scaling factor 1/Q and the corresponding numerical simulation cases are shown in Table 1. Fuel and air are well premixed before inlet via a standard premixer in experimental setup and it is also set to premixed in numerical simulation. The equivalent ratio is 0.7, the inlet temperature is room temperature and the pressure is 10,1325 Pa. According to formula 2, We have to notice that W_R will stay constant under such conditions. So in this study, Da_I law has a similar form with constant resident time law. But They are fundamentally different.

Experimental setup

The experiment was carried out on atmospheric high temperature rise and low emission burner test rig at Institute of Turbomachinery (TMI) in Shanghai Jiaotong University.

The experimental system is illustratated in Figure 2. Main air flow at atmospheric is supplied by a 11 kW fan and its temperature is maintained at around 25°C. The shape of premixer is similar to laval nozzle, making inlet air and fuel well premixed before going into the burner. Natural gas is supplied by a fuel tank and goes through the high precision mass flow controller of which the accuracy is $\pm 1\%$. In experiment study, the model combustor is 3/5 of the prototype. The flame pictures are captured by a digital camera equiped with a CH+ filter to catch flame (Migliorini et al., 2014). Experimental cases are listed in Table 2.

Case	Laws	1/Q	Inlet Velocity (m/s)	Re	Da _l
1	Prototype	1	45	1.37E + 05	76.48
2	Re	1/2	90	1.37E + 05	19.12
3	Da _l	1/2	22.5	3.42E + 04	76.48
4	Re	1/3	135	1.37E + 05	8.50
5	Da _l	1/3	15	1.52E + 04	76.48
6	Da _l	1/4	11.25	8.55E + 03	76.48
7	Da _l	1/5	9	5.47E + 03	76.48
8	Da _l	1/10	4.5	1.37E + 03	76.48

Table 1. Numerical study cases.



Fuel Supply System

Figure 2. Sketch of experimental system.

Table 2	2. Cases	in	experimental	study.
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Case	Inlet Velocity (m/s)	equivalent ratio	Re	Da _l			
Prototype							
1	25	0.6	6.2E + 4	8.42			
2	25	0.7	6.2E + 4	31.75			
3	25	0.8	6.2E + 4	63.52			
4	25	0.9	6.2E + 4	116.37			
5	25	1	6.2E + 4	200.83			
Model-Da law							
6	15	0.6	2.1E + 4	8.42			
7	15	0.7	2.1E + 4	31.75			
8	15	0.8	2.1E + 4	63.52			
9	15	0.9	2.1E + 4	116.37			
10	15	1	2.1E + 4	200.83			

Results and discussion

This section firstly compares the impact of the two applied scaling laws on the burner characteristics, when the burner is scaled from 1.0 to 1/3. This is followed by a scrutinize on the superior law at different scales from 1.0 to 1/10 and conclude the basic scaling rules. Finally the rules are validated through experiments.

Comparison of the impact of Re and Da_l

The impact of Re and Da_I on combustion state was then studied. Firstly, the influence of flow characteristics is analyzed. Figure 3 shows the streamline distribution. It illustrates that the streamline distribution obtained by Da_I modeling is highly similar to that of the prototype while Re law makes the length of the recirculation zone decreases. Then the influence on the flame characteristics is analyzed. Figure 3 shows the distribution of reaction progress variables obtained by the two laws modeling, which is used to represent the reaction zone and flame feature (Moëll et al., 2016). It can be seen that the flame shapes obtained by Da_I are relatively similar, but the ones obtained by Re method are relatively elongated. The flame will touch the wall when the scale is 1/2, and





the flame is seriously stretched and adhered to the wall when the ratio is 1/3. The mixture in the corner vortex region could not burn completely. This is due to the fact that when Re stayed constant, flow velocity in models is too high to stabilize the flame in the original position. The impact of Re is negative. It combustion state.

Analysis of the effect of Da_l law on geometric modeling

Next, the reaction state characteristics of different scaling under Da_I modeling are scrutinized. Because the Da criterion will lead to the decrease of the inlet velocity. This section studies the differences of different 1/Q when using the Da criterion.

Figure 4 shows the streamline distributions of different scales in the combustion state. It can be seen that the deviation of the flow field is not obvious when 1/Q = 1/2-1/5. However, when the prototype shrinked to 1/10, the flow field changes significantly: the penetration depth of the rotating jet is obviously weakened, the degree of adherence to the wall decreases, the expansion degree of the rotating jet increases obviously, and the jet appears to be wider and thicker. The shape of the recirculation zone also changes significantly, from "hammer" to "pear". Then, the impact on flame characteristics is analyzed. As shown in Figure 4. When the scale was reduced to 1/2-1/5, the flame shape is similar to the benchmark. But when the scale shrinked to 1/10, the flame becomes wider and shorter, and the expansion degree is also significantly weakened. This is because that the corresponding inlet velocity is too low and the flame propagation capacity is relatively enhanced, which leads to the flame position expanding and moving forward and outward. It can be seen that when 1/Q is too small and inlet velocity is too low, the combustion characteristics can not be well modeled.

Figure 5 shows the isometric axial velocity distribution at different scales in the reaction state. At 1/3D, it can be seen that the radial distribution of axial velocity obtained by all cases is basically the same, but with the increase of Q, the flow velocity outside the high-speed rotating jet decreases and the decline level increasing. When 1/Q = 1/4 - 1/5, the difference increases obviously. The reason is that the formation of shear layer is mainly related to the interaction between the rotating jet and the main recirculation zone, and the main recirculation zone is formed because of the rotating expansion. The rotating jet and main recirculation zone are similar, which makes the deviation of the inner shear layer small. However, the formation of outer shear layer is mainly related to the interaction between rotating jet and corner vortex, and the formation of corner vortex is mainly due to the geometry constraint. The boundary layer also has great influence. When Da_I is constant, Re decreases sharply, making the boundary layer thicker and angular vortex weaker, which weakens its influence on the deceleration outside the rotating jet. At the same time, the penetration jet is weakened. At 1D, it can be found that there are some deviations in the velocity distribution of all cases, but the trend is basically the same. At 5/3D, the velocity of the outer shear layer (near the wall) of the rotating jet decreases obviously with the increase of the scale, and the velocity distribution near the inner shear layer is slightly higher than the prototype. So the expansion degree of the rotating jet at this position of models is relatively weakened. At 7/3D, the velocity distribution is in good agreement with prototype. This is because low Re still inhibits the penetration and expansion of the otating jet to a certain extent.

Figure 6 shows the relationship between flame characteristics and 1/Q. The x-axis stands for the reciprocal of Q, indicating the scale degree; the y-axis stands for the key flow characteristics. With the increase of Q, the flame first lengthens and then shortens, while its expansion degree first decreases and then increases. When 1/Q = 1/3, the deviations of flame length and flame expansion angle are the largest, which are 3.04% and 5.97% respectively. This is because before 1/3, with the increase of Q, the velocity intensity gradually decreases and the recirculation zone weakens. But at this time, the velocity is still high and the flame is still mainly stabilized by the recirculation zone, which leads to the elongation and expansion of the flame; However, when 1/Q < 1/3, the flow velocity becomes weak, and the influence of flame propagation velocity on the stable position is relatively strong. Therefore, although the recirculation zone continues to weaken, the combined action of the backflow zone and the flame propagation makes the flame move forward and expand outward. It can be seen that, when 1/Q > 1/5, Re is not too low and Da_I is guaranteed, the difference of the flame length and expansion degree between model and prototype is not big.

Figure 7 shows a comparison of the flow characteristics at 1/2-1/5 scale in the reaction state.

With the increase of Q, the length of the recirculation zone shows a nonlinear shortening trend, but the overall difference is not big, and the maximum deviation is 3.1% when 1/Q = 1/5. This is because when the reduction ratio is below 1/5, the penetration and expansion degree of the rotating jet can be well ensured in the reaction state, although it is slightly weakened, it has little influence on the main recirculation area. Although the length of recirculation zone decreases with the increase of Q, its deviation is relatively small. As for the diameter of the recirculation zone, it first increases before the scale of 1/2, and then decreases, but the overall



Figure 4. Comparison of reacting flow under different scale under Da_l laws.

difference is not big. The maximum deviation is also 3.1% when the reduction ratio is 1/5, and the change of the radial position of the vortex center is almost consistent with it. In this case. When the reduction ratio is below 1/5, and because the radial dimension of the combustion chamber is relatively short, the geometric boundary has a strong inhibitory effect on the radial distribution of the rotating jet. The two factors makes the radial position of vortex center and the diameter of recirculation zone change little. However, this also causes the axial position of vortex center to move forward exponentially with the scaling factor, and then move backward when Q < 1/4. In this case, the maximum deviation of axial position of vortex center occurs at 1/4, which is 10.04%. This is because that the two-dimensional vortex center is the intersection point when the axial velocity and radial velocity reach zero at the same time, and the main recirculation zone is weakened, which also weakens the axial deceleration of the rotating jet, but the radial change of the rotating jet is relatively small due to the geometric boundary restriction, which leads to the vortex center pushing back. However, when Q = 5, the penetration ability of the rotating jet itself is too weak compared with other reduction ratios. Although the shear effect in the main recirculation region is also weak, the comprehensive effect makes the vortex center pushed back less than that at 1/4.



Figure 5. Axial velocity distribution of reacting flow of different scale under Dal.

Experimental study for validation of Da_l law

Based on the above conclusion, experimental study is carried out for validation. Because for both the prototype and model, flame features obtained from all cases seems the same. So only case 5 and case 10 are showed here. Figure 8 illustrates that the flame structures of prototype and model seem the same. Due to the position of



Figure 6. Comparison of flame characteristics under different scale under Da₁ law. (a) Flame angle (b) Flame length.



Figure 7. Comparison of flow characteristics of different scale under Da₁ law. (a) Recirculation zone length (b) Recirculation zone diameter (c) Eyespot radial position (d) Eyespot axial position.

camera, the flame tip height of the two cases seems have a little difference but the shape and angle is similar. Figure 9 shows the NOx emission of Prototype and model under full operating conditions. It can be seen that the trend of NOx emission changing with equivalent ratio is similar for both burner, which increases with the



Figure 8. Comparison of flame structures under Da₁ law. (a) Prototype (b) Model.



Figure 9. Comparison of NOx under Da_l law.

equivalent ratio. But the NOx of model is always higher than prototype. The probable cause is that the emission measuring point located at the outlet vent. When burner changed from prototype to model, the burner size and inlet velocity decreased, but the longth of cooling-jacket stayed the same, causing that the delay time increased in practice.

Figure 9 shows the NOx emission of Prototype and model under full operating conditions. It can be seen that the trend of NOx emission changing with equivalent ratio is so similar for both burner, which increases with the equivalent ratio. The NOx of model is slightly higher than prototype when equivalent ratio is low and slightly lower when equivalent ratio is high. This is because that Da law can keep a similar flow and combustion field, and residence time is also guaranteed.

Conclusions

In this paper, numerical simulation experiment are used to study the influence of different geometric scaling laws on combustion characteristics. The results show that:

As for non-combustion flow field, Re law could be a good choice. But Re law will cause significant increase of flow velocity causing the reaction distribution changes greatly. The flame will extended and expanded much more than prototype. Mixture in corner vortex region burn insufficient. With the increase of Q, the deviations increase. Da_I law will bring a moderate change to the flow field.

As for combustion flow field, Da_I can keep a good similarity. Although when 1/Q = 1/5 the axial position of eye point has a 10.04% deviation and the outer layer has a higher velocity distribution, but the consistency is still good. But when 1/Q = 1/10, Da_I law can not work well.

As for the flame shape, Re law will bring significant deviation while Da_I law can get similar flame shapes between 1/2-1/5. But when 1/Q = 1/10, flame will be much thicker and shorter than prototype.

As for NOx emission, Da_I law can get a very good consistency with prototype. Considering the above conclusions, It is suggested that Da_I law is suitable for lean premixed swirl combustor geometry scaling.

Nomenclature

Symbols

- D diameter (m)
- V velocity (m s⁻¹)
- W_R reaction rate (mol m³ s⁻¹)
- *Yf* mass fraction of fuel
- Q scaling factor

Greek

 ρ density (kg m⁻³) μ kinetic viscosity (pa s⁻¹)

Dimensionless groups

Re Reynolds number Da_I Damköhler first number

Abbreviations

DLE Dry low emission

Competing interests

Wenda Xie declares that he has no conflict of interest. Ting Shi declares that he has no conflict of interest. Bing Ge declares that he has no conflict of interest. Shusheng Zang declares that he has no conflict of interest.

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