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Review

Supersonic Combustion Modeling and Simulation on Genera Platforms

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Abstract: Supersonic combustion is an advanced technology for the next generation of aerospace vehicles. In the last two decades, numerical simulation has been widely used for the investigation on supersonic combustion. In this paper, the modeling and simulation of supersonic combustion on general platforms are thoroughly reviewed, with emphasis placed on turbulence modeling and turbulence–chemistry interactions treatment which are both essential for engineering computation of supersonic combustion. It is found that the Reynolds-averaged Navier–Stokes methods on the general platforms have provided useful experience for the numerical simulation in engineering design of supersonic combustion, while the large eddy simulation methods need to be widely utilized and further developed on these platforms. Meanwhile, the species transport models as a kind of reasonable combustion model accounting for the turbulence–chemistry interactions in supersonic combustion have achieved good results. With the development of new combustion models, especially those designed in recent years for high-speed combustion, the turbulence–chemistry interactions treatment for numerical simulation of supersonic combustion based on general platforms is expected to be further mature in the future.

Keywords: supersonic combustion; turbulence model; subgrid model; combustion model; numerical method

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1. Introduction

The hypersonic vehicle, which can fly at a speed higher than Mach 5, is a kind of advanced vehicle with significant research values at present and has broad application prospects in the future. The propulsion system needed for such an important vehicle has also been the focus of research. When the hypersonic vehicle flies in the atmosphere, it can use an air-breathing propulsion system which only needs to carry fuel without oxidant and has a large specific impulse. Therefore, the hypersonic air-breathing propulsion system has gradually become a research hotspot. In this type of propulsion system, the scramjet is an important component. The airflow in the scramjet combustor is supersonic, and the flow-through time of fuel and air in the combustor is only on the order of milliseconds. As a result, it is essential to realize effective mixing of fuel and air and maintain stable combustion in such a short period of time [1,2]. Over the decades, the field has proposed various approaches to solve these problems. Some researchers have proposed to adopt different fuel injection methods, such as transverse injection [3–5] and pulsating injection [6], to improve the mixing efficiency of fuel and air. Some researchers have studied the method of adding a cavity to the wall of the combustor to form a recirculation zone to enhance the mixing and stabilize the flame [7,8]. NASA proposed the concept of struts [9], which work well for improving mixing: the tip of wedge-shaped struts can induce shock waves which can effectively promote the mixing of fuel and air and the rear end of struts can form a small backflow area to facilitate the mixing [10,11]. Besides the above injection and flow-path innovation, some researchers study the flow parameters or boundary conditions of the combustor to find out the optimal flow conditions [12–14].

Most of the investigations on different aspects of supersonic combustion are carried out by experimental or numerical techniques. However, the equipment and cost needed for experimental research are beyond the capacity of most researchers. In recent years, with the rapid progress of computer technology and computation method, the results of numerical simulation are becoming more and more accurate and can be considered to investigate complex supersonic combustion [15–28]. Although numerical simulation cannot completely replace experimentation, it can be helpful in the initial type selection and subsequent design optimization of the combustor, which can greatly reduce the cost and speed up the research and development. On the acquisition of the overall performance parameters of the combustor, the results obtained by appropriate computation methods can be in good agreement with the experimental results. As for detailed phenomena in combustor turbulent flow fields, they can also be captured with a fine enough mesh, an appropriate mathematical model and a precise discrete scheme, demonstrating the effectiveness and importance of computational fluid dynamics (CFD) methods for numerical simulation of supersonic combustion.

As a branch of fluid mechanics, CFD develops gradually with computer technology. In the 1960s, it became an independent discipline. In the 1980s, with the emergence of the first generation of commercial software, CFD technology has made rich achievements in engineering design and has been recognized by the academic community. So far, there have been many successful general software platforms with different characteristics, which can provide solutions to various fluid problems. For the numerical simulation of supersonic combustion flow field, it can be solved by using the general software platforms with their various built-in turbulence models/subgrid models, combustion models and numerical methods, and some special requirements can be imported into the solver of the general software platform through the custom function.

In this paper, the supersonic combustion modeling and simulation based on the general software platforms are reviewed. The general platforms play an increasingly important role in solving this kind of complex problem and are also favored by the academic community. An obvious trend is that more and more studies on supersonic combustion are conducted using general platforms. In this review, the modeling and simulation methods used in these studies are summarized and compared with each other in order to provide some basic methods for solving supersonic combustion flow field on general platforms. This paper expounds four aspects of modeling and simulation. In Section 2, turbulence modeling in the numerical simulation of supersonic combustion is reviewed, mainly focusing on large eddy simulation (LES) methods and Reynolds-averaged Navier–Stokes (RANS) methods, two commonly used turbulence simulation methods. The principle and simulation results of different models are compared. This section is the key part of this review. Section 3 reviews the application of combustion models in the numerical simulation of supersonic combustion. Section 4 introduces the calculation of thermal physical properties of such flow fields. Section 5 reviews the numerical methods of spatial discretization and time advance in supersonic combustion. Conclusions and prospects are given in Section 6.

2. Turbulence Models and Subgrid Models

On the CFD general platforms, most of the turbulent flow problems can be solved by the RANS methods and the LES methods. With the appropriate combustion model, the flow field of supersonic combustion can also be well simulated. Although turbulence can be described by the Navier–Stokes (NS) equation, and most turbulence problems can be solved by Direct Numerical Simulation (DNS), the computational cost of complex flow with a high Reynolds number is unacceptable. In the currently most widely used RANS method, the NS equation is first averaged, and then the new unknown parameter, Reynolds stress, is depicted by an appropriate turbulence model to enclose the equation. General platforms offer a variety of options to make sure users can select different turbulence models according to different flow fields. For the LES method, it has become a popular solution in recent years. It first separates the large-scale eddy from the small-scale eddy by filter function, then calculates the large-scale eddy directly and solves the small-scale vortices by subgrid model. Although LES has the disadvantages of higher requirement for mesh fineness than RANS and not so accurate prediction for the near-wall region, its advantages of less cost than DNS and better accuracy than RANS will make it the most promising turbulence simulation method for engineering application in the next few years.

In the representative general platform Fluent, LES can adopt a variety of subgrid models, such as the Smagorinsky–Lilly (SL) subgrid model, wall-adapting local eddy-viscosity (WALE) subgrid model, wall-modeled large eddy simulation (WMLES) subgrid model, wall-modeled large eddy simulation S-omega (WMLES S-Omega) subgrid model, and dynamic kinetic energy/kinetic-energy transport (DKE/KET) subgrid model. The Smagorinsky model is the first subgrid model which was proposed by Smagorinsky in 1963, and it is the most widely used subgrid model. Del Rossi et al. [29], based on Fluent, used the Smagorinsky–Lilly model and fractal model (FM) to carry out an LES calculation on the SCRJ combustor in order to study the effects of these two subgrid models on supersonic combustion simulation. The results showed that there are some differences between the two models in the concentration distribution of reactants and products, but there is no substantial difference. Overall, LES did not reproduce a series of weak shock waves caused by intake section contraction, and this may have been caused by numerical diffusivity in the early days of the commercial code. On this basis, Ingenito et al. [30] from the same research group developed a new subgrid model, ISCM, which used Fluent as the platform to simulate two supersonic combustion test cases, and compared it with the aforementioned Smagorinsky–Lilly model and fractal model. It is found that the ISCM model has better agreement with the experimental data than the other two subgrid models. With the help of Fluent, Ingenito et al. [31] conducted a further study on the ISCM subgrid model. They analyzed the physical mechanism and deduction process of the model, which was developed specifically for supersonic combustion, and considered the effects of compressibility on reaction rate and mixing. The simulation with ISCM model is more accurate than the simple Smagorinsky model. Based on the flow field calculated by the ISCM model, the flame characteristics of supersonic combustion and the effects of Mach number and compressibility on turbulence and combustion were studied. The ISCM subgrid model proposed by Ingenito et al. is more suitable for the simulation of supersonic combustion than the encapsulated LES subgrid model of the early software. This is inevitable, for the general platform will first pay attention to the versatility of the plug-in model and to ensure that it has a certain solving ability for both compressible and incompressible flows. However, this also reflects the strong extensibility of the general platform that user-designed models can be inserted and solved through its UDF function, which can receive a quite accurate flow field.

In addition to the simple Smagorinsky–Lilly subgrid model, Fluent also has a built-in dynamic kinetic energy subgrid model for LES that takes into account the transport of subgrid turbulent energy and can better deal with subgrid-scale turbulence. Huang et al. [32] studied the inherent instability of combustion in the supersonic combustor of a rocket-based combined cycle (RBCC) engine with the LES and dynamic kinetic energy subgrid model of Fluent. They compared the LES results with the RANS results and experimental data and found significant differences between the two simulated results. Compared with the smooth temperature distribution simulated by the RANS method, LES can better capture the unstable process of supersonic combustion. The comparison also fully reflects the essential differences between RANS and LES, and the simulated results of LES are in better agreement with the experimental data. It is shown that LES with dynamic kinetic energy subgrid model has good performance in regard to the simulation of supersonic combustion. On this basis, Huang et al. [33] further analyzed the combustion oscillation characteristics of the same combustor model by using the same simulation method and obtained meaningful results. It is fully demonstrated that the general platform could achieve accurate simulation of supersonic combustion, and its built-in LES model can capture the instantaneous and unstable characteristics of combustion, as this is very helpful for numerical investigations on supersonic combustion.

Besides the general platform mentioned above, OpenFoam is another general platform frequently used for large eddy simulation of supersonic combustion. Chapuis et al. [20] and Nordin-Bates et al. [21] utilized the mixed model in OpenFoam to model the subgrid stress tensor and flux vectors in large eddy simulation equations, and they simulated the typical condition of HyShot II supersonic combustor. It was found that the wall-pressure and heat-flux data on both the cowl and body sides of the combustor agreed well with the experiment results. The mixed model of the large eddy simulation also performed well in other numerical case studies of supersonic combustion, such as in large eddy simulations of DLR supersonic combustor [22], NAL supersonic combustor [23] and LAPCAT II supersonic combustor [24].

Recently, Fureby [25] conducted a comparative study of subgrid models, reaction mechanisms, and combustion models in a large eddy simulation of supersonic combustion on OpenFoam. The influence of the subgrid model was first tested in simulations of the nonreacting case and compared with the experiment. It that found that the localized dynamic k-equation subgrid model and the hyperviscosity subgrid model performed better than the Smagorinsky subgrid model. Then the localized dynamic k-equation subgrid model was used for a reacting case to evaluate the influence of reaction mechanisms and combustion models. It was found that the localized dynamic k-equation subgrid model combined with J20 or Z22 reaction mechanisms and the PASR or SF combustion models could produce results that were in good agreement with the experimental data. This comparative study presents an excellent reference for large eddy simulation of supersonic combustion on general platforms.

Table 1 summarizes the subgrid models commonly used for supersonic combustion on general platforms. The practical characteristics and existing applications of these models are emphasized.

Table 1. Subgrid models commonly used for supersonic combustion on general platforms.

Model Names	Model Characteristics	Model Applications
• Smagorinsky model • Fractal model • ISCM model • Mixed model • Localized dynamic k-equation model • Hyperviscosity model	• LES with subgrid model usually performs better than RANS with turbulence model in supersonic combustion • Subgrid models considering compressibility effects perform better than those without these considerations in supersonic combustion • ISCM model, mixed model, and localized dynamic k-equation model can be used for detailed studies on supersonic combustion, using general platforms	• Strut-based supersonic combustor • Cavity and strut-based supersonic combustor • Simple-geometry supersonic combustor • Other supersonic combustors

For general turbulence problems, the RANS method is the most commonly used. It can provide the most economical method for complex flow simulations. In general software platforms, several turbulence models for the RANS method have been used for supersonic combustion flow simulations. There is no single turbulence model that is perfectly suitable for all turbulence problems, and users can make trade-offs based on flow characteristics, required accuracy, and available computational resources and time.

To simulate supersonic combustion by the RANS method on general software platforms, the commonly used turbulence models are two-equation models. Fluent has three built-in k–ε turbulence models, namely the standard k–ε model, the RNG k–ε model, and the Realizable k–ε model. The standard k–ε model solves the turbulent kinetic energy, k, and kinetic energy dissipation rate, ε, and uses the wall function to analyze the fluid velocity in the viscous sublayer near the wall. Considering the robustness of the standard k–ε model, Huang et al. [34,35] used it to simulate the supersonic combustion flow during the period of type selection, design optimization, and parameters' study on the propulsion system of the hypersonic vehicle. The simulated results are in good agreement with the experimental results, and subsequent research on the configuration of the flame stabilizer of the propulsion system based on this flow field has also achieved effective results. Although the standard k–ε model is helpful for the numerical simulation of some specific supersonic combustion flow, it is still obviously insufficient compared with other two-equation models, so it is not recommended by Fluent. Kummitha [36] took Fluent as the platform and took the scramjet combustor of the German Aerospace Center (DLR) as the research object. The standard k–ε model, SST k–ω model, and LES are used to simulate the combustion flow. Although the k–ε model is simpler to implement and converges faster, its prediction of shock wave is not good. In general, the performance of the SST k–ω model is better.

The RNG k–ε model is an improvement on the standard k–ε model by adding extra terms to the ε equation to consider the mean flow change of turbulent dissipation, which makes the calculation of flow more reliable and accurate. In the early days, Abdel-Salam et al. [37] used the RNG k–ε model to carry out numerical simulation of the dual-mode scramjet combustor with Fluent and captured some flow field structure. Huang [38] also used this model to carry out numerical simulation of the aforementioned DLR combustor, and the good agreement between the numerical results and the experimental data verified the reliability of this turbulence model for supersonic combustion simulation.

The Realizable k–ε model is also a variant of the k–ε model, which adds a formula to the turbulence viscosity and a new transport equation to the dissipation rate. It is the default recommended turbulence model in the mainstream commercial software platform. However, there is no conclusive evidence that it performs better than the RNG k–ε model. In the domain of supersonic combustion, many scholars have made a comparative analysis of these two turbulence models. Mattick and Frankel [39] conducted numerical simulation with Fluent for the study on the vitiation effects of supersonic combustion flow using these two models and found that they have their own advantages and disadvantages. In general, the Realizable k–ε model was better in predicting jet flow field, but both models were unsatisfactory in terms of reaction flow field, which might be caused by the defects of early Fluent platform and the simple combustion model. Luo et al. [40] took the DLR combustor as the research object and carried out the numerical simulation of supersonic combustion by using three two-equation models, namely the RNG k–ε model, Realizable k–ε model, and SST k–ω model. The results show that, compared with the Realizable k–ε model and the SST k–ω model, the RNG k–ε model is more suitable for the numerical simulation of the flow field in a typical scramjet combustor with strut. On the whole, the selection of the two-equation k–ε model should be carried out according to the characteristics of the flow field. For the simulation of supersonic combustion, the RNG k–ε model and Realizable k–ε model of Fluent perform better than the standard k–ε model; both of them have their own advantages and disadvantages, and they are both able to simulate supersonic flow field to a certain extent. Before performing large calculations, researchers can perform a test by using smaller cases of similar flow characteristics, and this is believed to be helpful for them to make better choices.

There are three types of k–ω models in the Fluent, which are the standard k–ω model, baseline (BSL) k–ω model, and shear-stress transport (SST) k–ω model. In the calculation of supersonic combustion, the SST k–ω model is the most common, as it combines the advantages of the k–ε and k–ω model, using a hybrid function based on the wall distance to ensure that the k–ω model is used in the near wall region, while the k–ε model is used in the area away from the wall. For example, Huang et al. [41] used the SST k–ω model to study the DLR combustor to examine the effects of different fuel injection temperatures and pressure on combustion flow and found that the variation of hydrogen jet parameters has obvious effects on the flow field. Although the calculation results are slightly different from the experimental data, they indicate that the SST k–ω model can simulate the overall parameters of the supersonic combustion flow with certain reliability and accuracy, making it suitable for the type selection and design optimization of the combustor.

The SST k–ω model not only performs well in Fluent, but also is often used in other general software platforms as a turbulence model to deal with supersonic combustion problems. Banica et al. [42] used this model in CFD++ software to study different combustion modes to optimize the design of combustor. The calculated results were consistent with the experimental data as a whole, with only some local deviations, which confirmed that commercial software packages could reduce the workload of designing a model supersonic combustor, but some characteristics of local flow would be omitted. The turbulence model was also used in CFD++ in the literature [43–45], the combustor performance parameters under different equivalence ratios were studied, and many results were obtained. In addition, Shekarian et al. [46] used the SST k–ω turbulence model on the OpenFOAM to study the effects of the interactions between shock wave and transverse jet on fuel and air mixing and flame stability, and they also obtained valuable conclusions.

Table 2 summarizes the turbulence models commonly used for supersonic combustion on general platforms. The practical characteristics and existing applications of these models are emphasized.

Table 2. Turbulence models commonly used for supersonic combustion on general platforms.

Model Names	Model Characteristics	Model Applications
• Standard k–ε model • RNG k–ε model • Realizable k–ε model • SST k–ω model	• These models can predict overall parameters of supersonic combustor • These models can predict some flow field structure in supersonic combustor • These models cannot accurately predict detailed flow characteristics in supersonic combustors • RNG k–ε model and realizable k–ε model perform slightly better than the standard k–ε model • SST k–ω model is the most commonly used turbulence model in simulating supersonic combustion and performs better than the standard k–ε model	• Strut-based supersonic combustor • Cavity-based supersonic combustor • Step-based supersonic combustor • Other supersonic combustors

3. Combustion Models

In addition to turbulence modeling, it is very important to adopt a suitable combustion model to treat turbulence–chemistry interactions for numerical simulation of supersonic combustion. For different combustion phenomena, the general platforms provide a variety of combustion models. For example, the models in Fluent for gas phase combustion include species transport model, non-premixed combustion model, premixed combustion model, partially premixed combustion model, and composition probability density function (PDF) Transport model. The species transport model solves the transport equation of each species, and the reaction rate calculated by the submodel is taken as the source term of the species transport equation. The species transport model is widely used in premixed combustion, non-premixed combustion, and partially premixed combustion, and it is also favored by researchers in the simulation of supersonic combustion. In the species transport model, Fluent provides four submodels for calculating the reaction rate, which are finite-rate model, finite-rate/eddy-dissipation model, eddy-dissipation model, and eddy dissipation concept (EDC) model.

The finite-rate model calculates the reaction rate by Arrhenius equation and chemical reaction mechanism data. In supersonic combustion, the chemical reaction timescale is not infinitely fast relative to the supersonic turbulence time scale; thus, it is reasonable to use the finite-rate model in the numerical simulation of supersonic combustion. Huang et al. [32] considered that the supersonic combustor of RBCC engine has the characteristics of premixed and non-premixed combustion modes and adopted the species transport model, in which the reaction rate is calculated by finite-rate model. They conducted a numerical simulation by finite-rate model combined with the spray model (to simulate the atomization of liquid kerosene) to study the combustion mechanism. The finite-rate model has attracted much attention not only on the Fluent platform, but also on OpenFOAM [46] and CFD++ [43–45], so many scholars use it to simulate supersonic combustion.

In the study of two kinds of combustor, Mattick and Frankel [39] adopted the finite-rate model, based on the detailed reaction mechanism, and the eddy-dissipation model, based on the global reaction mechanism and EDC model, respectively. For the coaxial jet combustor, the Composition PDF Transport model was adopted. The results show that the EDC model did not produce a flame, and the finite-rate model based on detailed reaction mechanism performed better than the eddy-dissipation model based on global reaction mechanism.

The eddy-dissipation model used in the abovementioned works from the literature is suitable for the rapid fuel combustion process, and the overall reaction is controlled by the turbulent mixing rate, while the chemical reaction rate is ignored. Generally, it is only used for single-step or two-step reaction mechanisms. Moreover, it can be used only for non-premixed combustion because it ignores the effects of molecular transport and chemical kinetics characteristics. The EDC model is a more precise and detailed combustion model, allowing the use of detailed reaction mechanisms. It takes into account both the timescales of turbulence and chemical reactions, but it requires a large amount of computation. Del Rossi et al. [29] used the EDC to simulate the interaction between turbulence and chemical reaction with the global reaction mechanism of hydrogen. The calculated results show a different flame anchoring mechanism from the experiment, and perhaps the results could be improved by combining the EDC model with a more detailed reaction mechanism.

Considering the chemical dynamics and turbulence factors, the finite-rate/eddy-dissipation model combines the finite-rate model with the eddy-dissipation model. It calculates the Arrhenius rate and mixing rate at the same time, and the smaller one is used for turbulent combustion. This model is widely used in the simulation of supersonic combustion [4,34–36,38,40,41]. It can be used in combination with LES and the RANS method, which is only applicable to single-step or two-step reaction mechanisms. It is very suitable for the type selection and design optimization of supersonic combustor due to its relatively low amount of calculation. The finite-rate/eddy-dissipation model combined with the appropriate turbulence model and fine mesh can also capture some flow field structure of supersonic combustion, thus making it a very practical combustion model.

In general, the supersonic combustion numerical simulation methods of the general software platforms have a variety of combustion models. In recent years, the most commonly used supersonic combustion numerical simulation model is the species transport model, which can be applied to a variety of combustion modes, including premixed, non-premixed, and partially premixed combustion. Because the timescale of chemical reaction in supersonic combustion is not infinitely fast compared with the timescale of supersonic turbulence, the finite-rate model and the finite-rate/eddy-dissipation model are more commonly used in the submodels of the species transport model for numerical simulation of supersonic combustion. According to the needs of the researchers, the global reaction mechanism with lower computational cost can be placed in the finite-rate/eddy-dissipation model, and the multistep reaction mechanism with more complete reaction details can be placed in the finite-rate model for the numerical simulation of supersonic combustion.

Table 3 summarizes the combustion models commonly used for supersonic combustion on general platforms. The practical characteristics and existing applications of these models are emphasized.

Table 3. Combustion models commonly used for supersonic combustion on general platforms.

Model Names	Model Characteristics	Model Applications
• Finite-rate model • Finite-rate/eddy-dissipation model • Eddy-dissipation model • Eddy dissipation concept model	• Finite-rate/eddy-dissipation model is the most commonly used combustion model in simulating supersonic combustion on general platforms • Finite-rate model can well represent the real process of supersonic combustion • Eddy-dissipation model is not so suitable for supersonic combustion • Eddy dissipation concept model usually needs to be used with detailed reaction mechanism in order to perform well • For lower-cost computation of supersonic combustion, finite-rate/eddy-dissipation model with global reaction mechanism is recommended; for detailed computation of supersonic combustion, finite-rate model with detailed reaction mechanism is recommended	• Strut-based supersonic combustor • Cavity and strut-based supersonic combustor • Step-based supersonic combustor • Simple-geometry supersonic combustor • Other supersonic combustors

4. Thermophysical Property Calculation Methods

In order to accurately simulate the supersonic combustion flow field, the calculation of the thermal physical properties of the fluid is also very important. Thermal physical properties of fluid components and mixtures generally include density, specific heat capacity, viscosity, thermal conductivity coefficient, mass diffusion coefficient, etc. To accurately simulate the flow field, the properties of components and mixtures must be set in accordance with the real physical conditions.

In the supersonic flow field, gases are compressible and are considered to conform to the ideal gas law, and their density can be set as ideal gas. Abdel-Salam et al. [37] defined the density, viscosity, and thermal conductivity of the hydrogen–air mixture with ideal gas mixing, while the specific heat capacity, viscosity, and thermal conductivity of individual components were all defined as polynomials of temperature. Based on the OpenFOAM platform, Qin et al. [12] used Fourier heat conduction law and Fickian species diffusion law to calculate the thermal physical properties under the assumption that the gas mixture is linear viscous and optical thin. Zhang et al. [47] also used Sutherland's law to calculate the dynamic viscosity, and the Eucken Approximation was used to calculate the thermal conductivity. Sutherland's law establishes a relationship between the dynamic viscosity and the absolute temperature of ideal gas, which is widely used at present and has quite good accuracy. In addition to what was mentioned earlier, Fureby [25] and Wu et al. [48,49] also used Sutherland's law to calculate viscosity. In addition, thermal conductivity and mass diffusivity can be obtained from viscosity based on the assumption that Prandtl number and Schmidt number are constant [25,48,49].

5. Numerical Methods

The general platforms usually adopt different numerical methods to solve various flow problems. For the numerical simulation of supersonic combustion, the applicability of the numerical method is an aspect that needs to be discussed in detail, which is of great significance for the stability, convergence, and accuracy of the simulation.

In the typical general platform Fluent, there are two kinds of numerical methods. One is the pressure-based segregated solution algorithm, which is generally used for incompressible flow and weakly compressible flow. For high-speed compressible flows, another kind of coupled solution algorithm based on density is generally adopted. The simulation of supersonic combustion flow field based on Fluent platform mostly adopts this solver [29–31,34,39,50–52]. Fluent provides two convective flux types when using the density-based solver. One is Roe flux-difference splitting (Roe-FDS), which can reduce the dissipation in LES; the other is the advection upstream splitting method (AUSM), which can more accurately describe shock waves and expansion waves and is more commonly used in the simulation of supersonic combustion [38]. Roe-FDS belongs to the flux difference splitting (FDS) method, which, together with flux vector splitting (FVS), is the upwind scheme used in the early years. The former has poor robustness and relies on entropy correction, while the latter has the defect of insufficient resolution. The hybrid flux difference scheme AUSM combines the advantages of FVS and FDS and has the high precision of FDS and the stability of FVS.

The first-order upwind scheme, second-order upwind scheme, QUICK scheme, and third-order MUSCL scheme are commonly used for spatial discretization of convection terms. The choice of discretization scheme depends on the computational accuracy and mesh. When the flow direction is consistent with the grid direction, the structural mesh can adopt the first-order upwind scheme, which has low accuracy but high stability and high convergence rate. When the flow direction is not aligned with the grid, the unstructured mesh generally adopts second-order upwind scheme to obtain more accurate results. However, it takes longer for calculation than the first-order upwind scheme, and its convergence is worse. QUICK and third-order MUSCL provide higher accuracy than the second-order upwind scheme with respect to rotation or swirling problems, but for general problems, the accuracy of their calculations will not be significantly improved.

For supersonic combustion, the spatial discretization generally adopts the second-order upwind scheme [29,30,32,33,42–45], and the precision is sufficient for the calculation of general supersonic flow field. However, for the complex three-dimensional flow field, Ingento et al. [31,50–52] adopted the third-order MUSCL scheme, which is a hybrid of the central difference scheme and second-order upwind scheme. The MUSCL scheme in Fluent improves the accuracy of space marching by reducing numerical diffusion. For the choice of discrete format, sometimes it can also be used comprehensively. For the problem of poor convergence, the first-order upwind scheme can be adopted firstly, and then it can be switched to the higher-order scheme. In earlier studies, Mattick and Frankel [39] adopted the segregated solution method to calculate the supersonic combustion problem due to the defective of the solver. For the discretization of the governing equation, the first-order upwind scheme was adopted first, and then the QUICK scheme was adopted after the residual was reduced by two orders of magnitude. No problem of difficult convergence was encountered in the calculation.

The appropriate time marching scheme should be considered in the numerical simulation of unsteady state. Ingenito et al. [30] set the time step as 10^{-8} s and adopted a second-order time-precise scheme. Huang et al. [32] used the semi-implicit second-order Crank–Nicolson method with a time step close to 1 μs. In another paper [33], they used the fully implicit second-order Crank–Nicolson method with a time step of less than 1 μs. There are also many studies using the steady-state solution [42–45]. The Crank–Nicolson method is an implicit second-order method for solving heat equations and similar partial differential equations in time, and it is unconditionally stable for the diffusion equations. In addition to Huang et al. [48,49], Wu et al. [48,49] also used the second-order Crank–Nicolson method. Qin et al. [12] adopted an explicit second-order total variation diminishing (TVD) time integration scheme, and the time step was set as 10^{-8} s. Zhang et al. [47] used a smaller time step of 10^{-9} s to make the CFL number less than 0.1. Fureby [25] adopted the Runge–Kutta time integral scheme for time marching.

6. Conclusions and Prospects

Numerical simulations of supersonic combustion are being carried out more and more broadly in the field of aerospace engineering. In this paper, the modeling and simulation of supersonic combustion based on a general platform were reviewed, and the conclusions and prospects are as follows:

(1) Numerical simulation of supersonic combustion based on a general platform in recent years has been able to obtain reasonable dynamical, thermal, and combustion parameters, thus providing valuable basis for supersonic combustor design.
(2) The Reynolds-averaged Navier–Stokes methods based on general platform can be used for preliminary engineering design of supersonic combustor, but their accuracy for the prediction of details of supersonic combustion is not sufficient.
(3) Large eddy simulation methods are suitable for the numerical simulation of supersonic combustion on a general platform when considering both accuracy and computational cost/time burden, and they are recommended to be utilized in future studies on supersonic combustion.
(4) In the numerical simulation of supersonic combustion based on a general platform, the species transport models as a kind of reasonable combustion model accounting for the turbulence–chemistry interactions in supersonic combustion achieved good results. With the development of new combustion models, especially those designed in recent years for high-speed combustion [53], the turbulence–chemistry interactions treatment for numerical simulation of supersonic combustion based on general platforms are expected to be further mature in the future.
(5) In the numerical simulation of supersonic combustion based on a general platform, the effects of the thermal physical property calculation methods and the numerical methods should be systematically investigated.

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