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Research on Quantitative Evaluation Method of Scramjet and Integration

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ABSTRACT

The objective of this paper is to develop a method for the advancement quantitative evaluation of scramjet and hypersonic vehicle/scramjet integration. By studying the theory of analytic hierarchy process (AHP), a new method to build the quantitative evaluation system was established. The theory of Nondimensional parameter was also proposed and the results showed that this calculation method is scientific and effective. Both the numerical simulations of the advancement quantitative evaluation of scramjet and hypersonic vehicle/scramjet integration were carried out with a number of calculation examples and the advancements of different projects were obtained, which proved the feasibility and reliability of the evaluation method. This quantitative evaluation method simples the complex problems of scramjet and integration evaluation and lays the foundation for the further research of hypersonic technology.

Keywords: AHP; Quantitative evaluation; Scramjet and integration

NOMENCLATURE

Symbols

Fs	Specific thrust [N]
Fa	Thrust per frontal area [N]
Ma_0	Flight Mach number [-]
Ma_{cru}	Cruising Mach number [-]
η_0	Total efficiency [-]
η_b	Combustion efficiency [-]
ΔP_m	Pitching moment different between cold and heat state [N•m]
ΔMa	Starting Mach range [-]
T	Temperature [K]
P	Pressure [Pa]
Q	Dynamic pressure
W/S	Wing load
Γ	Empty weight ratio
Isp	Specific impulse [-]

Subscripts

max	Maximum value
cor	Corrected value
bp	Value at relay point

1.0 INTRODUCTION

The research of hypersonic vehicle and scramjet has entered the stage of the flight test and engineering development in recent years [1-2]. An important issue at this stage is how to solve the contradiction between the power demand of the hypersonic vehicle and the performance of the power system. The issue reflects in two aspects: one is the advancement evaluation of power system when choosing the appropriate power for hypersonic vehicle, the other is considering the technical risk of the scram-jet and integration when choosing the appropriate power system. Therefore quantitative evaluation problems of advancement and technical risk of scramjet and the hypersonic vehicle/scramjet integration are becoming increasingly prominent.

Analytic hierarchy process (AHP) is a simple, flexible and practical multiple criteria decision-making method, which was carried out by an American operations researcher T.L.Saaty [3] in 1970s. AHP has the advantages of simple principle, solid theoretical principle and small calculation error, therefore it is widely used in decision-making. The research of AHP in aerospace field has developed in recent years. Walter Hammond [4] applied AHP to space transportation systems. Chen Jie [5] took liquid rocket engines as research objects and gave the method of determining the weighted factor by quantitative analysis and AHP. Zhang Wei [6] established a top-level model of aero engines based on AHP and carried out the quantitative evaluation results of different engine projects.

The objective of this article is to develop a method of quantitative evaluation of scramjet and integration combined with calculation models of scramjet and the integration of hypersonic vehicles [7-8] which is based on the lumped parameter method and the AHP methodology. This article built quantitative evaluation systems of the scramjet and the integration and got the evaluation results by some calculation examples to analyze the feasibility and reasonability of the method.

2.0 METHODS

2.1 Analytic hierarchy process

AHP is used as an analytic method of multi-objective decision making, which is combined with both quantitative analysis and qualitative judgments to evaluate the scheme. Firstly, the complex problem is divided into several different components, and the component factors are grouped by dominance relationship and the hierarchical structure is built; then factors are pairwise compared and weights are calculated to determine the relative importance of each factor; finally the researchers make a comprehensive judgment according to the number of weight and determine the relative importance of different objects.

2.1.1 Hierarchical structure

The structure includes the objective layer, the criterion layer, the index layer and the project layer. The objective layer is on the top of the hierarchical structure, which has only one element of the goal of the problem; the criterion layer contains the factors that need to be considered in the process of achieving the goal; the index layer is the index to describe the content of the criterion layer; the bottom layer, that is project layer, is the alternatives that can achieve the goal. The hierarchical structure can be formed in different kinds, a tree-like hierarchical structure is built in this paper to simplify the complexity of the quantitative evaluation system.

2.1.2 The pairwise comparison matrix

Assuming the upper layer element C dominates the lower layer element u_1, u_2, … , u_n, the weight of u_i is its relatively importance to C. each alternative is assessed by pairwise comparison for its relative contribution or effectiveness each criterion and then the pairwise comparison matrix is built, which includes proportional matrix (see in equation 1) and inversely proportional matrix (see in equation 2) . If the element is an abstract concept, experts grade the weight between 1 and 9 according to the relative contribution.

Proportional matrix:

$$A=\begin{pmatrix} \frac{u_1}{u_1}=1 & \frac{u_1}{u_2} & \cdots & \frac{u_1}{u_n} \\ \frac{u_2}{u_1} & \frac{u_2}{u_2}=1 & \cdots & \frac{u_2}{u_n} \\ \cdots & & \frac{u_i}{u_j} & \cdots \\ \frac{u_n}{u_1} & \frac{u_n}{u_2} & \cdots & \frac{u_n}{u_n}=1 \end{pmatrix} \quad \ldots(1)$$

Inversely proportional matrix:

$$A=\begin{pmatrix} \frac{u_1}{u_1}=1 & \frac{u_2}{u_1} & \cdots & \frac{u_n}{u_1} \\ \frac{u_1}{u_2} & \frac{u_2}{u_2}=1 & \cdots & \frac{u_n}{u_2} \\ \cdots & & \frac{u_j}{u_i} & \cdots \\ \frac{u_1}{u_n} & \frac{u_2}{u_n} & \cdots & \frac{u_n}{u_n}=1 \end{pmatrix} \quad \ldots(2)$$

2.1.3 Weight calculation and consistency test

The calculation of elements' weight of each layer with AHP is shown in Figure 1. The pairwise comparison matrix of each element is build and the maximum eigenvalue and eigenvector are calculated by power iteration method. If the consistency test is satisfied, the eigenvector is used as the weight of the underlying element to the upper element.

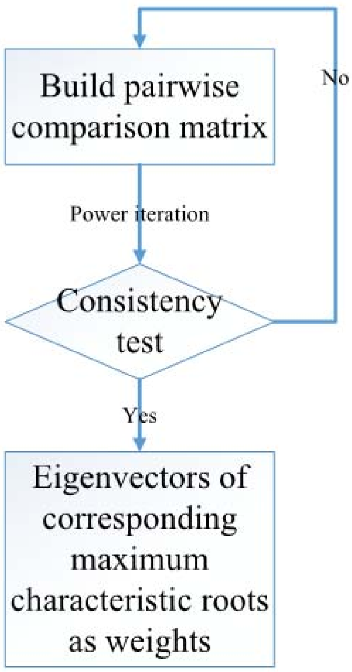

Figure 1 the flow chart of calculating weight

Researchers' knowledge of things is diverse and complex, they can't take other elements, such as element C and D, into account when element A and B is compared. Therefore there may be contradiction between elements which causes the inconsistency of the matrix and leads to the error of the eigenvalues and eigenvectors of the matrix. The consistency index *CI* is introduced to judge the consistency of the matrix, see equation (3):

$$CI=\frac{\lambda_{\max}-n}{n-1} \quad \dots(3)$$

$\lambda_{\max}$ in equation (3) introduces the maximum eigenvalue of the pairwise comparison matrix. The consistency of the matrix is accepted if $CI<0.1$, otherwise a new pairwise comparison is began to structure the matrix.

2.2 Nondimensional parameter

The evaluation element are physical values, the pairwise comparison can't show the relatively importance directly by comparing values. Taking scramjet A and B for an example, their unit thrust at design point respectively are 49kgf/(kg/s) and 56kgf/(kg/s), their total efficiency respectively are 0.4025 and 0.46, the ratio of advancement which is calculated by taking these values is shown in equation(4):

$$\frac{P_B-P_A}{P_A}\times 100\%=\frac{56-49}{49}\times 100\%=\frac{0.46-0.4025}{0.4025}=14.3\% \quad \dots(4)$$

Equation (4) shows that these two parameters share the same advancement, however it's relatively easier for the improvement of the unit thrust than the one of the total efficiency. This method of pairwise comparison can't show the real relationship between elements.

This paper presented a method of nondimensional parameter in the base of engineering upper limit and lower limit of scramjet performance parameter calculated by lumped parameter method to solve this problem. The upper limit is assumed to be 100 point and the lower limit is 60 point, the point of certain parameter *X* is calculated by equation (5):

$$X=40.0\times\frac{P-P_{\min}}{P_{\max}-P_{\min}}+60.0 \quad \dots(5)$$

In equation (5), *P* represents the parameter value, P_{max} represents the maximum value, P_{min} represents the minimum value. If the parameter increases gradually with the development of technology, P_{max} corresponds the upper limit and P_{min} is the lower limit; otherwise P_{max} means the lower limit and P_{min} is the upper limit.In the above example, the nondimensional points of the unit thrust are:

$$X_A=40.0\times\frac{P_A-P_{\min}}{P_{\max}-P_{\min}}+60.0=40.0\times\frac{49-47}{76-47}+60.0=62.8 \quad \dots(6)$$

$$X_B=40.0\times\frac{P_B-P_{\min}}{P_{\max}-P_{\min}}+60.0=40.0\times\frac{56-47}{76-47}+60.0=72.4 \quad \dots(7)$$

The nondimensional points of the total efficiency are:

$$X_A' = 40.0 \times \frac{P_B - P_{\min}}{P_{\max} - P_{\min}} + 60.0 = 40.0 \times \frac{0.4025 - 0.382}{0.49 - 0.382} + 60.0 = 67.6 \quad \ldots(8)$$

$$X_B' = 40.0 \times \frac{P_A - P_{\min}}{P_{\max} - P_{\min}} + 60.0 = 40.0 \times \frac{0.46 - 0.382}{0.49 - 0.382} + 60.0 = 88.9 \quad \ldots(9)$$

The improvement of the unit thrust is:

$$\frac{72.4 - 62.8}{62.8} \times 100\% = 15.3\% \quad \ldots(10)$$

And the improvement of the total efficiency is:

$$\frac{88.9 - 67.6}{67.6} \times 100\% = 31.5\% \quad \ldots(11)$$

Equation (10) and equation (11) show that this method can obtain more objective comparison results.

The nondimensional point of the inversely proportional matrix is：

$$X = 100.0 - 40.0 \times \frac{P_{\max} - P}{P_{\max} - P_{\min}} \quad \ldots(12)$$

The definitions of P_{max} and P_{min} in equation (12) are the same as those in equation (5).

3.0 MODELING AND CALCULATION

Based on the theory of operational research methodology, how to evaluate the advancement of different scramjet or integration schemes was studied in this section. Taking into account that AHP theory is the most widely used in large decision problems, this paper adopted the method to the quantitative evaluation of the scramjet and the integration.

3.1 Scramjet quantitative evaluation

The parameters of scramjet and integration are firstly introduced and the essential characteristics of parameters are revealed in order to select suitable evaluating parameters and structure the quantitative evaluation system. Then two different projects are taken as calculation examples to study the quantitative evaluation methods of scramjet.

3.1.1 System modeling

The quantitative evaluation of scramjet advancement is of great significance in the scheme design and selection. Due to the development of scramjet is still in the early stage of engineering application, the aspects of safety, reliability, maintainability and so on were not evaluated in this paper, the evaluation model mainly focuses on scramjet performance.

In evaluating the applicability of scramjet, the selection of evaluation elements should follow the following principles:

1. parameters that characterize engine performance should be chosen as evaluation factors;

2. In addition to considering the dynamic performance, economic factors should also be taken into account, which has a certain impact on the future development and engineering application of scramjet.

3. The stability of scramjet is a premise of providing reliable power supply for hypersonic vehicles, and the stability also determines the complexity of the control system. Therefore researchers should pay attention to the related parameters that affect the stability of scramjet.

According to the above principles, the evaluation elements of the quantitative evaluation of scramjet advancement are selected as the following 8 parameters presented in Table 1.

Table 1

Eight evaluation elements of scramjet evaluation

Element	**Nomenclature**
Specific thrust	F_s
Thrust per frontal area	F_a
Specific impulse	I_{sp}
Total efficiency	η_0
Pitching moment difference between cold and heat state	ΔP_m
Maximum temperature	$T_{\max}$
Maximum pressure	$P_{\max}$
Starting Mach range	ΔMa

The quantitative evaluation system of scramjet advancement built in this paper is shown in Figure 2.

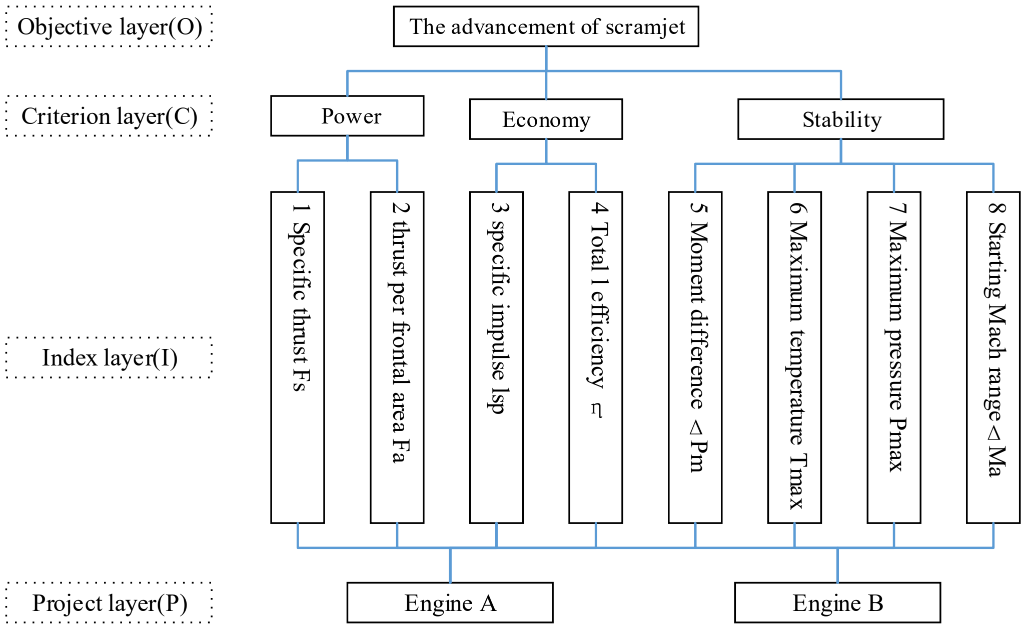

Figure 2 the structure of the quantitative evaluation system of the scramjet

3.1.2 Evaluation calculation

There are nine matrixes for the quantitative evaluation of scramjet advancement, including one matrix of objective layer, three matrixes of criterion layer and five matrixes of index layer. Taking the matrix of objective layer (matrix *O*) for an example, the matrix is formed by pairwise comparing the relative contribution of three elements (power performance, economic performance and stability) in criterion layer to the objective layer element, which is shown in equation 13:

$$O=\begin{bmatrix} \frac{Power}{Power} & \frac{Power}{Economy} & \frac{Power}{Stability} \\ \frac{Economy}{Power} & \frac{Economy}{Economy} & \frac{Economy}{Stability} \\ \frac{Stability}{Power} & \frac{Stability}{Economy} & \frac{Stability}{Stability} \end{bmatrix} = \begin{bmatrix} 1 & 3.2 & 1.6 \\ 0.3125 & 1 & 0.5 \\ 0.625 & 2 & 1 \end{bmatrix} \quad \ldots(13)$$

The eigenvector of matrix *O* is obtained by power iteration and the relative weights of power performance, economic performance and stability are (0.516, 0.162, 0,322), the results are reliable through consistency test. The calculations of other matrixes are similar. Two hypothetical scramjet engines A and B were given in the calculation of elements' weight of project layer to index layer, which are shown in Table 2.

Table 2

Parameters of hypothetical engines

	Ma_0	N_1+N_2	Ma_2	A_{35}/A_3	A_4/A_3	A_9/A_0	η_b	Ma_{cor}
Engine A	6.0	2+1	3.15	1.2	2.0	1.4	0.85	4.0
Engine B	6.0	3+1	3.2	1.1	2.0	1.5	0.85	6.0

In Table 2, Ma_0 represents flight Mach number of design point; *N1+N2* represents mix-compression inlet, N_1 and N_2 represent the number of shock waves; Ma_2 represents Mach number of inlet outlet; A_{35}/A_3 represents the expansion ratio of first section of the combustor; A_4/A_3 represents the total expansion ratio of the combustor; A_4/A_3 represents the area ratio between the outlet of the nozzle and the inlet of the inlet; η_b represents combustion efficiency; Ma_{cor} represents correctd Mach number. The performance parameters were calculated by lumped parameter method.

According to the logical relationship between different layers, the comprehensive evaluation of two projects can be obtained after calculating the weights of project layer to index layer. The evaluation results of two engine schemes are shown in Table 3.

Table 3

The evaluation results of two scramjet schemes

Objective layer	The advancement of scramjet							
Criterion layer	Power		Economy		Stability			
Weights	0.516		0.162		0.322			
Index layer	F_s	F_a	Isp	η_0	ΔP_m	T_{max}	P_{max}	ΔMa
Weights	0.667	0.333	0.750	0.250	0.182	0.286	0.435	0.097
Quantitative coefficient of A	0.764	0.862	0.764	0.752	0.983	0.784	0.963	0.822
Quantitative coefficient of B	0.837	0.881	0.838	0.896	0.979	0.778	0.931	0.765
Comprehensive index of A	82.48%							
Comprehensive index of B	86.09%(better)							

And Figure 3 shows the visual comparison of the elements' relative weights of two schemes.

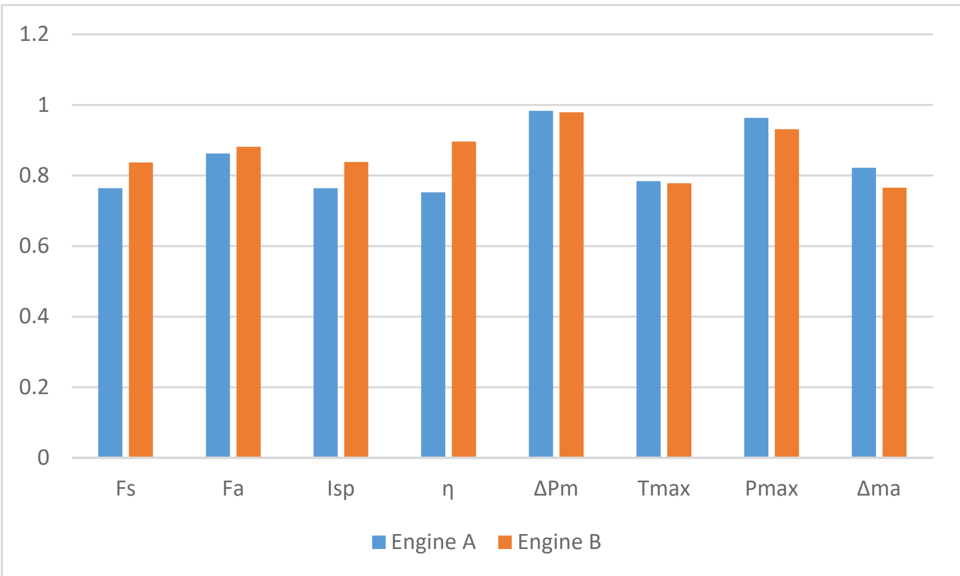

Figure 3 the comparison of elements' weights of two schemes

The evaluation value of project A is 0.8248 and the evaluation value of project B is 0.8609, which means project B is more advanced. Comparing the data of Table 3 and Figure 3, the weights of two scramjets are approximately the same in terms of stability. However, in terms of power performance and economic performance, engine B is better than engine A. In general, scheme B is more advanced than A in quantitative evaluation.

3.2 Integration quantitative evaluation

The scramjet and hypersonic vehicle are highly integrated in the structure and they are inseparable in performance, therefore it's necessary to study the quantitative evaluation of the advancement of scramjet/hypersonic vehicle integration.

3.2.1 System modeling

The quantitative evaluation of integration needs to consider the integration performance, the realizability of schemes, the engineering constraints, the project support and the cost analysis. Integration performance is an important factor of evaluate whether the integration scheme is advanced and whether the vehicle can complete the flight mission. Due to the integration involving multidisciplinary problems, the feasibility of the evaluation system should be considered. In addition, it's necessary to consider the engineering constraints of the integration, which will limit the integration performances. The structure of the vehicle and the scramjet can affect the stability of the whole system, a scientific layout will help to balance the vehicle and engine. Since there are only a few successful experimental projects of scramjets, this paper only paid attention to the first three elements, that is integration performance, realizability and engineering constraints.

The criterion elements include 3 elements and the index elements include 12 elements, such as total weight, voyage and payload, in this paper. The structure of the quantitative evaluation system of integration advancement is shown in Figure 4.

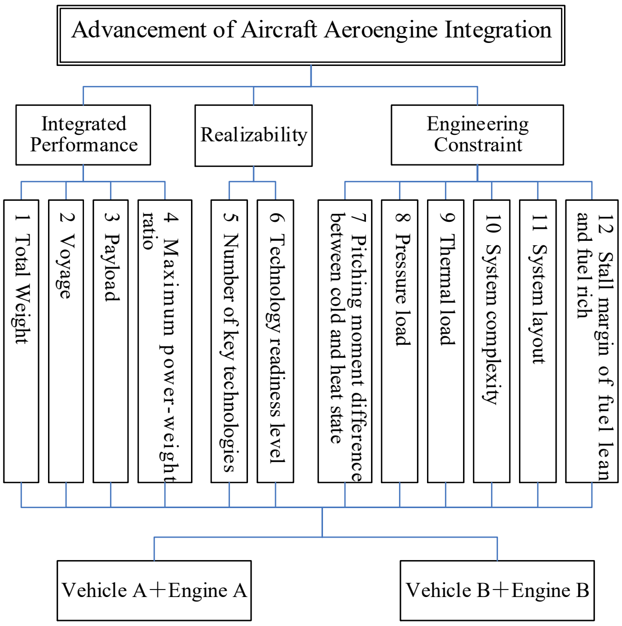

Figure 4 the structure of the quantitative evaluation system of the integration

3.2.2 Evaluation calculation

There are 16 matrixes for the quantitative evaluation of integration advancement, including one matrix of objective layer, 3 matrixes of criterion layer and 12 matrixes of index layer. Taking the matrix of objective layer (matrix *O*) for an example, the matrix is formed by pairwise comparing the relative contribution of three elements in criterion layer to the objective layer element. Since the greater the value of each element of criterion layer, the contribution to its total target, the matrix is proportional, which is shown in equation 14.

$$O=\begin{bmatrix} 1 & 3.0 & 1.6 \\ 1/3 & 1 & 0.7 \\ 0.625 & 1.429 & 1 \end{bmatrix} \quad \dots(14)$$

The eigenvector of matrix O is obtained by power iteration and the relative weights of integration performance, realizability and engineering constraints are (0.546, 0,185, 0,268), the results are reliable through consistency test. The calculations of other matrixes are similar. The two hypothetical scramjet engines A and B mentioned in the last section are also used in the calculation of elements' weight of project layer to index layer, and two hypothetical vehicles A and B were given to complete the calculation, which are shown in Table 4. The project layer include project C (engine A+ vehicle A) and project D (engine B+ vehicle B).

Table 4
Parameters of hypothetical vehicles

	Ma_{bp}	Q_{bp}（pa）	Ma_{cru}	W/S（kg/m^2）	Γ
Vehicle A	4.0	50000.0	6.0	5050.0	0.4
Vehicle B	4.2	80000.0	6.0	8050.0	0.3

In table 3, Ma_{bp} is Mach number in the relay point, Q_{bp} is dynamic pressure in the relay point, Ma_{cru} is the cruising Mach number, W/S is the wing load and Γ is empty weight ratio.

Table 5
The evaluation results of two integration schemes

Project layer → Index layer		Index layer → Criterion layer			Criterion layer → Object layer
Project C	**Project D**		**Integration**		
0.4182	0.5818	Total weight	0.1820		
0.4286	0.5714	voyage	0.2863	0.5462	
0.4878	0.5122	Payload	0.4348		
0.5035	0.4965	Maximum power-weight ratio	0.0969		
Project C	**Project D**		**Realizability**		
0.6032	0.3968	The number of key technologies	0.3333	0.1851	**Integration advancement quantitative evaluation**
0.4382	0.5618	Technology readiness level	0.6667		
Project C	**Project D**		**Engineering constraints**		
0.8768	0.1232	Pitching moment difference between cold and heat state	0.1031		
0.7260	0.2740	Pressure load	0.0903	0.2687	
0.5122	0.4878	Thermal load	0.1638		
0.4152	0.5848	Stall margin of rich or poor oil	0.2837		
0.3750	0.6250	System structural configuration	0.2193		
0.5455	0.4545	System complexity	0.1398		

According to the logical relationship between different layers, the comprehensive evaluation of two projects c and D can be obtained after calculating the weights of project layer to index layer. The evaluation results of two integration schemes are shown in Table 5.

The evaluation value of project C is 0.4811 and the evaluation value of project D is 0.5189 by calculation, which means project D is more advanced. Comparing the data of Table 5, the weights of two projects are approximately the same in terms of realizability and engineering constraint. However, project D is better than project C in terms of integration performance. In general, project D is more advanced than C in quantitative evaluation.

4.0 Conclusion

In this paper, a new method of the quantitative evaluation of scramjet and integration was established. This paper built the advancement quantitative evaluation system and the numerical simulation was carried out by the theory of analytic hierarchy process. In addition, the method of Nondimensional parameter was proposed and the results showed that this calculation method is scientific and effective. The advancements of scramjet and integration were evaluated with a series of calculation examples and the results of evaluation were obtained.

This method of quantitative evaluation simplifies the complex and difficult quantitative problems of scramjet and integration to a process of quantitative analysis and numerical simulation, which is of great significance to the development of hypersonic technology. What's more, the evaluation system can be expanded and improved with the development of hypersonic technology, which lays a theoretical foundation for the further research.

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