Numerical Simulation of Reynolds Number Effect of Transport Aircraft Considering Low-temperature Real Gas Effect

Hui Zhao, Yueyue Yang, Yaobing Zhang *, Jiantao Wang, Bin Mou

Computational Aerodynamics Institute, China Aerodynamics Research and Development Center, Mianyang 621000, China

* Corresponding Author Email: zhyb_super@sina.cn

Abstract. In order to study the effects of low-temperature real gas effects and Reynolds number effects on the aerodynamic characteristics of typical transport aircraft, in this paper we developed a RANS simulation software suitable for simulating the low-temperature and high-pressure real gas effects of nitrogen based on the ARK equation. CHNT-1 was used as the standard model for calculation, and the reliability of the program calculation results was verified by comparing them with the experimental results at room temperature. The calculation results under different Reynolds numbers at low temperatures show that within the range of pressure and temperature involved, the effect of real gas on the aerodynamic characteristics of the transport machine is very small, and can be ignored compared to the effect of Reynolds numbers. The experimental study of low-temperature wind tunnels using nitrogen as the medium can adopt the perfect gas hypothesis.

Keywords: Cryogenic real gas, rans simulation software, numerical simulation.

1. Introduction

The temperature of low-temperature pressurized high Reynolds number wind tunnel drives by nitrogen gas is in the range of 110-323K. Real gas effect will occur at such low temperatures. Its state equation does not satisfy the perfect gas assumption. Low-temperature real gas effect will affect the aerodynamic characteristics of different high Reynolds number configurations to some extent. At the same time, under this condition, the applicability of the traditional Sutherland formula for calculating the viscous coefficient also needs further verification. Aiming at this problem, we intend to develop fine simulation technology of numerical simulation oriented to real experiment conditions of low-temperature pressurized wind tunnel to realize real simulation of experiment conditions of wind tunnel and provide technical support for design of wind tunnel experiment scheme and correction of relevant experiment data in this paper.

The most accurate equation describing the thermodynamic state of real gas at low temperature is the virial equation [1] expressed in series form. The equation accurately describes the gas properties by increasing the number of terms. However, the virial equation is too complex to be realized by programming. Generally speaking, equation of state in the form of cubic equation is widely used in any gas or liquid, and its accuracy can basically satisfy the requirements of Engineering development. In this paper, Aungier-Redlich-Kwongz equation [2] (ARK equation) in the form of cubic equation is used to describe its thermodynamic characteristics in view of the low temperature state of nitrogen medium. Meanwhile, when solving the numerical equation, it is necessary to modify the enthalpy value, constant pressure specific heat coefficient, and other parameters of low-temperature nitrogen gas, taking into account the relevant physical properties parameters. According to the research results of relevant literature [3], 5 coefficient or 7 coefficient interpolation can be used to satisfy the requirements of low temperature wind tunnel condition simulation. In the study of viscosity coefficient and thermal conductivity correction of low-temperature nitrogen, it is planned to modify the viscosity coefficient and thermal conductivity coefficient of low-temperature nitrogen medium conditions to satisfy the needs of numerical simulation of low-temperature nitrogen medium.

Based on the ARK equations, we developed the numerical simulation technology of low-temperature non air medium, conducted numerical simulation research on typical configurations in wind tunnel experiments, and simulated the impact of low-temperature real gas effects and Reynolds number effects on aircraft aerodynamic characteristics under wind tunnel experiment conditions.

2. Numerical Method

The calculation in this paper mainly involves the steady calculation, which is carried out by using NNW-FlowStar, a subtranssonic flow field resolver independently developed by CARDC. NNW-FlowStar solver is a large-scale parallel flow field solver based on grid-centered unstructured mixed grids and Reynolds mean NS equations. It can use any shape grid unit and has more flexibility. The finite volume method is used to discrete the space, and the unknown variable is located at the center of the grid element. Implicit LU-SGS method is used for the calculation in this paper. Roe format is used for space convection term and SST two-equation model is used for turbulence model.

The integral form of the NS equation in the conservative form of three-dimensional Cartesian coordinates is as follows:

$$\frac{\partial}{\partial t}\int_{\Omega}\vec{W}d\Omega+\oiint_{\partial\Omega}(\vec{F}_c-\vec{F}_v)dS=0 \tag{1}$$

$\vec{W}$ represent conserved variables, $\vec{F}_c$ represents inviscid flux and $\vec{F}_v$ represents viscous flux.

For low temperature and high pressure gases with real gas effect, the ARK equation can be selected as the thermal state equation, and the corresponding calorimetric state equation can be derived from the thermodynamic relationship. The equation of state for ARK gases can be expressed in the following specific forms:

$$p=\frac{RT}{v-b_0+c_0}-\frac{a(T)}{v(v+b_0)} \tag{2}$$

Where b_0 and c_0 are constants related to the critical pressure and temperature of the gas, p is pressure, T is temperature, v is specific volume, and

$$\begin{aligned}
&a(T)=a_0\left(\frac{T}{T_c}\right)^{-n}\\
&a_0=0.42747R^2T_c^2/p_c\\
&b_0=0.08664RT_c/p_c\\
&c_0=\frac{RT_c}{p_c+\frac{a_0}{v_c(v_c+b_0)}}+b_0-v_c\\
&v_c=1/\rho_c
\end{aligned} \tag{3}$$

Where the subordinate "c" represents the critical parameter, a_0 is a constant related to the critical pressure and temperature of the gas, and R is a gas constant. In the standard Redlich-Kwong equation of state, the exponent n is 0.5. In the ARK equation of state, it is replaced by a general form. The optimum value of exponential n is related to pure matter. Aungier gives the values of 12 experimental data sets and uses the eccentric factor. The best fitting polynomial for temperature index n is provided as follows:

$$n=0.4986+1.1735\omega+0.4754\omega^2 \tag{4}$$

Eccentricity factors must be provided when performing the ARK model and can be estimated from the critical point and steam pressure curves using the following formula:

$$\omega = -\log_{10}\left(\frac{p_v}{p_c}\right) - 1 \tag{5}$$

Where the steam pressure p_v is calculated at state $T=0.7T_c$. In addition to the critical point pressure, the above formulas also need to understand the correlation of steam pressure as a temperature function.

The critical parameter for nitrogen is

$$T_c = 126.2K \quad p_c = 3.39\times10^6 Pa \quad \rho_c = 314.03kg/m^3 \tag{6}$$

Using the thermodynamic relationship and the concept of deviation function, the analytical expression of enthalpy is derived as follows:

$$h = h^0(T) + pv - RT - \frac{a(T)}{b_0}(1+n)\ln\left(\frac{v+b_0}{v}\right) \tag{7}$$

h^0 is the enthalpy when nitrogen is treated as a thermally complete gas. The specific pressure heat capacity of nitrogen is derived from the partial derivation of temperature by the expression of enthalpy:

$$\begin{aligned} c_p &= \left(\frac{\partial h}{\partial T}\right)_p \\ &= c_p^0(T) + p\left(\frac{\partial v}{\partial T}\right)_p - R - \frac{da(T)}{dT}\frac{(1+n)}{b_0}\ln\left(\frac{v+b_0}{v}\right) + a(T)(1+n)\frac{\left(\frac{\partial v}{\partial T}\right)_p}{v(v+b_0)} \end{aligned} \tag{8}$$

Where c_p^0 is the constant pressure specific heat coefficient of the complete gas. The interpolation formulas of 5 and 7 coefficients have been used in literatures, but their applicable temperatures range from 200K to 6000K. It is found that the equation of state with 5 coefficient agrees better with NIST data at low temperature. Sutherland's formula can be used for the viscosity coefficient and heat conductivity of nitrogen in the temperature range calculated in this paper.

After applying the ARK equation, the expression of sound velocity can be derived from the thermodynamic relationship:

$$a^2 = \frac{\rho h_T}{\rho h_T \rho_p + \rho_T(1-\rho h_p)} \tag{9}$$

3. Simulation and analysis

3.1 Model and Grid and Calculation Conditions

The CHNT-1 standard model is used for the test. As shown in the figure below, AeCW-1 medium standard grid is used with 17.377 million meshes, including 84.399 million tetrahedral units, 8.883 million triangular prism units and 54,000 pyramid units. The normal first grid spacing of the boundary layer is 1.0e-6m, the normal growth rate is 1.2, and the number of grid units at the rear edge of the wing is 12.

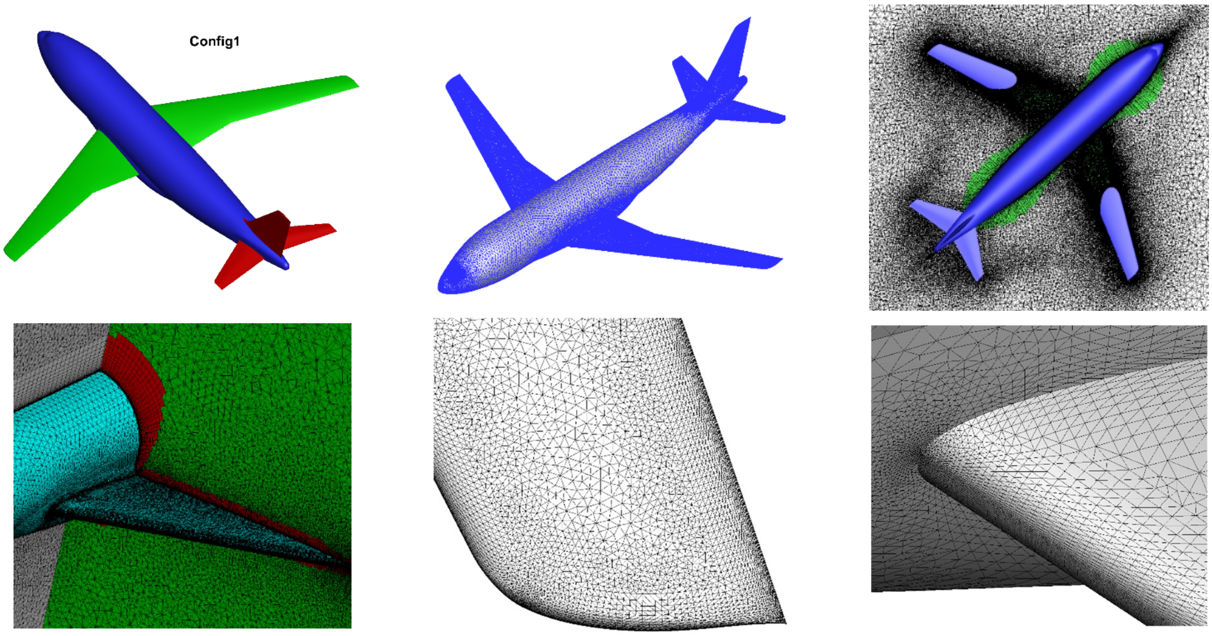

Figure 1. Standard model and grid distribution of CHNT-1

3.2 Effects of Nitrogen and Air Media on Aerodynamics Characteristics

The effects of nitrogen and air medium on aerodynamics at room temperature and pressure were investigated. *Ma*=0.78, *Re*=3.3e6 (based on average pneumatic chord length), reference temperature 297.04K (75F), angle of attack alpha=0, 1, 2, 3, 3.5, 3.75, 4, 4.25, 4.5, references are as follows:

Table 1. Reference of aerodynamic coefficient

Reference area(m^2)	0.25784
Reference length(m)	0.1937
Reference point(m)	(0.66087, 0.0, 0.0)

The calculation results are shown in the figure below. It can be seen from the comparison curves that under the normal temperature and pressure experiment Reynolds number condition, the difference between the calculation results of nitrogen medium using real gas and that of air medium using perfect gas is very small. The lift-drag coefficient is in good agreement with the experiment results. Due to the influence of the experiment tail support, the calculated pitch moment has a translation of about 0.035 head-up moment relative to the test results.

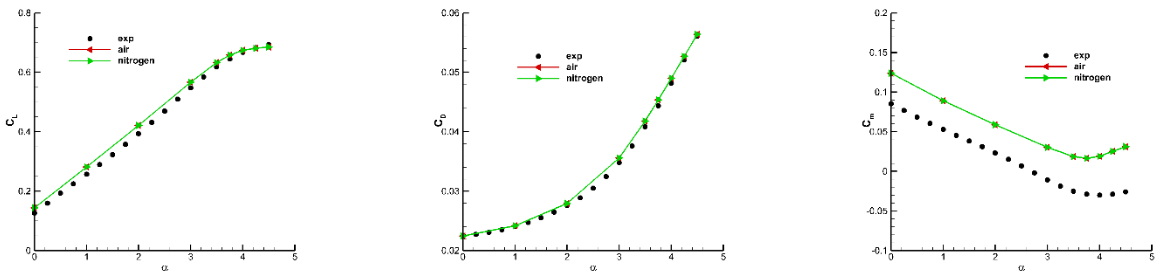

Figure 2. The influence of different medium on aerodynamics

3.3 Effects of Real Gas Effects on Aerodynamic Characteristics

The aerodynamic characteristics of a full-size aircraft configuration with Ma=0.78 and a height of 10 km (Table 2, case 1, air medium) are calculated firstly. Then, considering the flow of real gas effect, the scale model in the low-temperature wind tunnel is simulated under two conditions (Table 2, case2&case3, medium is nitrogen, static temperature is between 100K and 150K) which satisfy Ma=0.78 and Reynolds number of 2.46816658776e7. The aerodynamic characteristics of the two conditions are compared and analyzed to study the effect of real gas effect. In order to compare the influence of real gas effect with that of Re number, case 4 is applied, working condition of case 4 is air inflow, temperature is normal, model is scaled, and Reynolds number is reduced to 3.3e6.

It can be seen from Figure 3 that under the same Mach number and Reynolds number, the calculation results of lift, drag and pitch moment coefficient are very consistent. At 0 degrees of attack, the drag difference of operating conditions under case 1~3 is less than 0.1 count, which indicates that the low-temperature real gas effect has very little effect on the aerodynamic characteristics of the transport plane in the temperature range of low-temperature wind tunnel. For case 4, the difference of aerodynamic characteristics is very obvious when the Reynolds number differs by 7.5 times.

Table 2. Different conditions parameters with different case

	case1	case2	case3	case4
Medium	air	nitrogen	nitrogen	air
Ma number	0.78	0.78	0.78	0.78
Re number	2.4681666e7	2.4681666e7	2.4681666e7	3.3e6
Pressure (10^5Pa)	0.26499765	1.5860966	2.8900621	0.98748478
Temperature (K)	223.25214	100.0	150.0	297.04
Density(kg/m^3)	0.41350837	5.5192905	6.6062606	1.1581195
Sound of spend (m/s)	299.53176	200.32194	247.64536	345.50356
Reference length (m)	3.724	0.1937	0.1937	0.1937

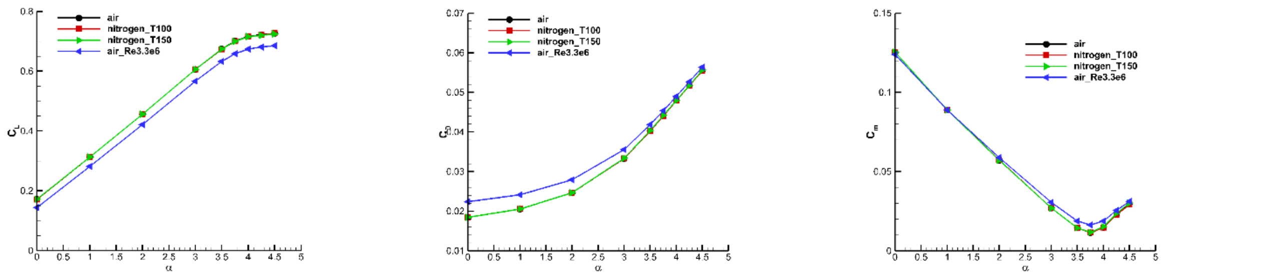

Figure 3. Comparison of calculation results under different conditions

Figure 4 shows the pressure distribution cloud and streamline on the upper surface of the wing under 4 operating conditions with 3 degrees of attack. It can be seen that under the same Reynolds number, the pressure distribution under case 1~3 of operating condition are very close and the difference in separation zone length are very small. For operating condition 4(case 4), the shock wave position moves forward and the separation zone length is significantly longer due to the smaller Reynolds number.

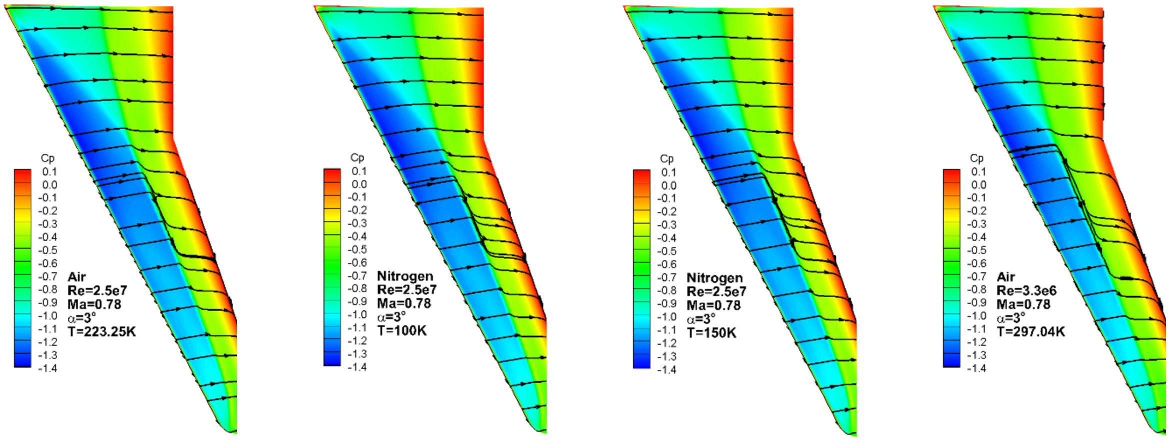

Figure 4. Pressure distribution cloud and streamline on the upper surface

4. Conclusion

In summary, under low-temperature and high pressure conditions, the ideal gas state equation is quite different from the low-temperature gas state equation, but in the pressure and temperature range involved, the low-temperature real gas effect has little effect on the aerodynamic characteristics of the transport plane. Compared with the Reynolds number effect, it can be neglected. The perfect gas assumption can be used in the low-temperature wind tunnel experiment study with nitrogen as the medium.

References

[1] Epstein P S. Textbook of thermodynamics[M]. New York, London,1961.

[2] Augnier R H. A fast accurate real gas equation of state for fluid dynamics analysis applications[J]. Journal of Fluids Engineering, 1995.

[3] McBride B J. NASA Glenn coefficients for calculating thermodynamics properties of individual species[R]. NASA TP-211556, 2002.