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二级入轨载机小涵道比涡扇发动机探讨

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【摘要】　对五种涡轮发动机的概念研究表明：小涵道比涡扇发动机与冲压发动机组合，适于用作二级入轨载机的动力装置。

关键词:　涡轮风扇发动机　复合式发动机　航天飞机

1　五种涡轮发动机方案的比较

在 $Ma=3.5\sim4$ 以下采用涡轮发动机有明显的优点。为此我们对空气涡轮火箭（ATR）、火箭风扇（RF）、叶尖涡轮方案（TTF）、氢膨胀涡轮（TSHE）和涡扇（TF）五种方案进行了分析比较。为使比较公平合理，各方案的性能、尺寸和重量计算全部采用相同的方法和标准。

性能计算：全部烧氢燃料，地面设计点空气流量全取 300kg/s，风扇压比全取 3.2。尺寸和重量计算采用同一方法（重量计算误差大多在±5%以内），而且对相同部件均选用相同材料，风扇和压气机全用钛合金，其余部件全部选用合金钢。计算重量时均不计入外部管路和附件重量。另外，风扇叶尖切线速度（对叶尖涡轮方案则为涡轮叶尖速度）也基本相同，以使风扇盘所受拉应力水平相同。

表 1 和图 1、2 给出了部分计算结果和三种发动机沿轨迹 B 的计算结果。由表 1 可见，叶

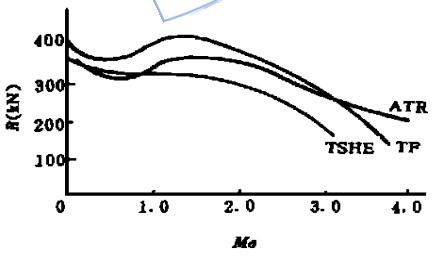

图 1　推力随 Ma 的变化

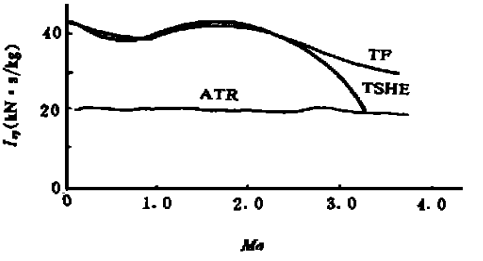

图 2　比冲随 Ma 的变化

尖涡轮方案重量最重（因风扇盘所受的拉应力比其它方案大好几倍），比冲最低，既使提高涡轮前温度，比冲最多只能达到 20kN·s/kg 左右，没有竞争力。火箭风扇方案推重比最高，比冲最低，因燃气从风扇叶片内部流过，受材料限制不能提高燃气温度（现为 922K），只能在高速飞行时靠发动机对液氢换热的加强减少液氧消耗。因此提高比冲有限，所以只适于加速

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型的飞行器。例如，高超音速拦截机，不适于用作二级入轨载机的动力装置。涡扇与氢膨胀涡轮方案在推力、比冲、重量方面基本相当，相差无几。还可发现，涡扇方案的推重比比反旋 ATR 低 27%，但比冲高 127%。

表 1 五种方案地面设计点性能比较

参 数	符号	单位	反旋 ATR	氢膨胀涡轮	叶尖涡轮	火箭风扇	涡 扇	涡扇 I
空气流量	G_a	kg/s	300	300	300	300	300	300
涵 道 比	$\bar{G}_a$		0.000	5.000	0.000	0.000	1.083	0.28
风扇压比	Π_f		3.2	3.2	3.2	3.2	3.2	4.0
高压压比	Π_{hp}			2.6			2.81	2.25
涡轮前温度	T_{03}	K	1262.2	300 (HP) 1040 (LP)	922	922	1800	1800
涡轮进口压力	p_{03}	MPa	2.229	2.736 (HP) 0.843 (LP)	4.413	4.413	0.870	0.871
高压涡轮落压比	Π_{th}			3.15			1.41	1.32
低压涡轮落压比	Π_{tL}		4.423	2.27	10.5		1.84	1.57
加力温度	T_{06}	K	2610.7	2520.1	2207.7	2261.2	2450	2450
燃料流量	G_f	kg/s	19.49	8.732	37.58	37.58	8.736	8.716
加力推力	R	kN	372.0	379.6	411.9	418.1	378.5	429.3
比 冲	I_s	kN·s/kg	19.09	43.47	10.96	11.12	43.32	49.26
单位推力	R_{sp}	kN·s/kg	1.24	1.26	1.37	1.39	1.262	1.43
发动机总重	W_e	kg	1975.4	2791.1	3819.3	1515.9	2787.6	2787.6
推 重 比	$\bar{W}_e$		21.4	13.9	11.0	28.1	13.8	15.7

由图 1、2 可见，当 $Ma<4$，氢膨胀涡轮方案的推力比涡扇低 10%（29.4kN）到 34.7%（98.1kN）。当 $Ma\leq 2.2$，两方案比冲相差不超过 2.6%（1.569kN·s/kg）。当 $Ma>2.2$，氢膨胀涡轮方案的比冲随 Ma 下降的幅度比涡扇大。当 $Ma=3$ 时，比冲比涡扇低 22.8%（5.884kN·s/kg）。从性能和重量全面衡量，涡扇比氢膨胀涡轮好。

涡扇与 ATR 相比，当 $Ma<4$，比冲比 ATR 高 60%～110%；当 $Ma\leq 3.25$，推力比 ATR 高，最多高出 16.9%（63.7kN）；当 $Ma>3.25$，推力比 ATR 低，而且 Ma 越大低得越多。从性能来看，在 $Ma=3.25$ 以下，涡扇优于 ATR。

经过 5 种循环方案的比较，我们认为，ATR 发动机因比冲低，推重比高，更适于单级入轨或加速型飞行器。而对于涡轮工况只用在 $Ma=3.5$ 以下的二级入轨载机的组合发动机来说，比冲更加重要。虽然涡扇的推重比比 ATR 低 27%，但比冲比 ATR 高一倍以上。按平均比冲估算，由于比冲的提高，从起飞到冲压接力点，涡扇可比 ATR 节约燃料 30t 左右，比冲带来的好处远远大于推重比降低 27%的不利影响。而且涡扇的推力在 $Ma=3.25$ 以下也优于 ATR，所以涡扇比 ATR 更适于与冲压发动机组合用作二级入轨载机的动力装置。

为检查涡扇发动机能否完全满足载机的性能要求，我们重新选择了涡扇的循环参数（见表 1 最末一列），进行了性能计算。

2　涡扇发动机性能

性能计算结果见图 3、4。计算使用的调节规律是等风扇物理转速、等涡轮前温度和变喷口喉道面积，并取非设计点加力温度为 2500K。由于高 Ma 飞行时完全膨胀的喷口面积太大。

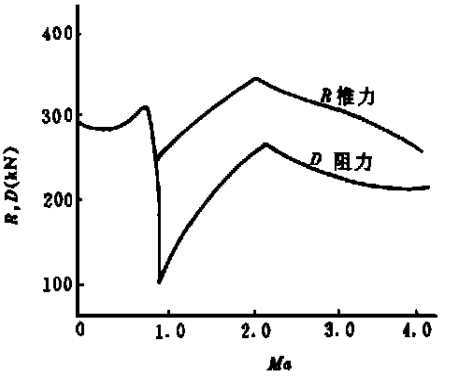

图 3　沿轨迹 A 推力和阻力随 Ma 的变化

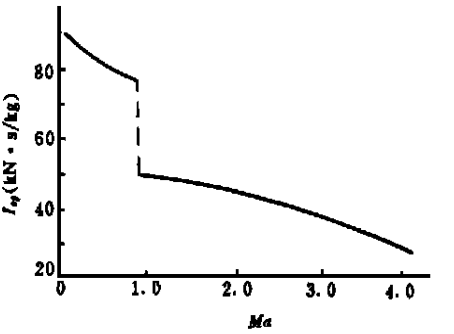

图 4　沿轨迹 A 比冲随 Ma 的变化

而喷口出口面积的选取牵涉到发动机的布局和飞机/发动机一体化设计问题，一时定不下来，所以暂时按以下喷口面积计算推力：当 $Ma \leq 1.0$，按完全膨胀计算推力；当 $Ma > 1.0$，按简单收敛可调喷口计算推力，再考虑引射喷口的推力增益回收推力 15%。另外，为避免低空超音速飞行对居民的干扰和提高比冲，在 $Ma = 0.9$ 以下和高度 9km 以下不使用加力状态，而使用最大状态工作。图 3 给出发动机沿轨迹 A 飞行时推力和单台发动机需承担的飞机阻力随 Ma 的变化。由图 3 可见，在 $Ma < 3.5$ 时，剩余推力处处大于 68.65kN，如载机装 6 台发动机总剩余推力可大于 411.88kN，能满足剩余推力要求。图 4 给出比冲随 Ma 的变化。由图 4 可见，当 $Ma \leq 3.5$，比冲都大于 31.63kN·s/kg；在 $Ma \leq 0.9$ 时，比冲都大于 73.55kN·s/kg，比冲都比较高，从性能上说，小涵道比涡扇发动机能满足二级入轨载机的性能要求。

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NUMERICAL ANALYSIS OF 3-D TURBULENT FLOWS IN 90 °BENDS

Xi Guang, Shang Hong, Wang Shangjin (*Xian Jiaotong University*)

ABSTRACT The 3-D turbulent flows in 90 °bends with different cross-sections have been analyzed with incompressible, time-averaged N-S equation. The capability of k-ε turbulence model for predicting the flow field with very strong curvature has been verified by the pipe bend (R_c/D= 0.87) experimental data made by the authors. Calculations of 3-D flow field in a 90 °duct bend and a 90 °pipe bend are presented. The results show that, before occurrence of the low velocity area formed mainly by the interchange of secondary flows near the inner wall, the mean velocity field predicted by the k-ε turbulence model is proved in reasonably good agreement with the experimental data even though the curvature of bends is very strong. But as soon as the above-mentioned low velocity area appears, the prediction accuracy of the k-ε turbulence model greatly drops down.

APPLICATION OF SUBMERGED VORTEX GENERATORS FOR SEPARATION CONTROL OF A SUBSONIC DIFFUSER

Chen Xiao and Jing Ping (*Nanjing Aeronautical Institute*)

ABSTRACT The effects of the main geometrical parameters of the submerged vortex generators on the diffuser performance are analysed. A combination of corotating and counter-rotating votex generators was used in the study. In the center part of the channel, four pairs of counter-rotating vortex generators were used to eliminate the flow separation. At the two corners, two corotating vortex generator blades and one pair of counter-roataing blades were used respectively to improve the three-dimensional separation flow fields in these corner regions. The experimental results show that the static pressure recovery coefficient C_P is enhanced remarkably and the total pressure loss is also reduced, if the geometrical parameters and the location of the vortex generators are selected properly. A comparative study between the submerged vortex generators of concave shape and the conventional vane-type vortex generators is also presented. Both of them have almost the same efficiency for separation control, but the parasitic drag of the former is less due to its submergence in the boundary layer; and it is convenient for practical application because its distance to the separation starting point on the diverging wall of the generator is much shorter.

TURBOFAN WITH A SMALL BYPASS RATIO FOR FIRST STAGE OF A TWO- STAGE TO- ORBIT VEHICLE

Yang Kaitian (*Shenyang Aeroengine Research Institute*)

ABSTRACT As turbomachinary is superior to rocket and ramjet at lower flight speed, a computational analysis of five sorts of hydrogen-fueled turbomachinary, i. e. ATR engine, rocket fan, tip turbine fan, two-spool hydrogen expander engine and turbofan has been accomplished. The results show that the turbofan with small bypass ratio is superior to the others in the performance at flight Mach number below 3.5. After choice of better cycle parameters, further performance calculation of the turbofan has been carried out. The total residual thrust of six engines is shown to be more than 411.88kN at flight Mach number below 3.5. It is indicated that the specific impulse of the engine is more than 31.63kN · s/kg at flight mach number below 3.5 and 73.55kN · s/kg at flight Mach number below 0.9 respectively. This type of turbofan combined with a ramjet is proved to be suitable for a powerplant

in the first stage of a two-stage to-orbit vehicle.

EFFECT OF THERMODYNAMIC PARAMETERS ON PERFORMANCE AND COST OF TURBINE ENGINE

Wang Rugen (*Air Force College of Engineering*)

ABSTRACT A method for estimating life cycle cost of aircraft turbine engine manufactured in China is provided on the basis of a statistic technology and a definition of life cycle cost ratio has been used. Changes in thrust, specific fuel consumption and life cycle cost have been calculated when thermodynamic parameters (π_k^*, T_3^* and T_{af}^*) and mean time between overhauls of the engine increase. It was found that there was a marked growth of the engine thrust when T_3^* increased, but life cycle cost ratio of the engine should, too, quickly grow. In order to make the growth of life cycle cost ratio acceptable for the Air Force, mean time between overhauls and total operation time of the engine must be lengthened. And a overhigh pressure ratio of the compresser often makes the thrust drop down and life cycle cost ratio grow up.

RESEARCH ON AIRCRAFT LIFE CYCLE COST REDUCTION

Wang Rugen (*Air Force College of Engineering*)

ABSTRACT On the basis of cost data collected from factories and the Air Force, the variation of life cycle cost is analyzed for the fighters in which one of four kinds of engine is installed respectively. It has been found that there should be a marked drop in the aircraft life cycle cost, if the suitable fund is allocated to increasing reliability, decreasing specific fuel consumption and lengthening time between two overhauls of the aircraft engine.

RESEARCH ON ALTITUDE SIMULATION OF STARTING FOR A SINGLE- SPOOL SMALL TURBOJET

Zhu Qing (*Aerospace Ministry*)

ABSTRACT Altitude simulation ignition tests of a single-spool small turbojet starting were completed at an altitude test rig. Some conclusions from the test data analysis have been drawn. It is very useful to supply secondary oxygen jet for high-altitude ignition and starting. The use of high energy igniter improves ignition and starting performance and reduces starting time. Fuel flow must be matched with air flow during the high-altitude starting. The fuel flow must be controlled by the rotational velocity of the rotor to limit temperature t_4^* and to avoid hang-up during the starting.

A DESIGN OF A ROTATING PROBE FOUR-AXIS TRAVERSE MECHANISM

Zhang Hong, Jiang Haokang, Xiao Ling, Xing Shuchu
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ABSTRACT A mechanism fully controlled by computer and stepping motor can move a probe in four axes (Null, Radial, Tangential and Axial) for completing flow measurement inside the rotor passage of the turbomachine during rotation. The mechanism can also move the probe for flow measurement inside the stator passage as a fixed one. The technical characteristics, principle of operation, construction design and running balance of the mechanism are discussed in detail.