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WZ-5 发动机改装高温涡轮的试验研究及分析

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【摘要】 WZ-5 发动机改装 WJ5A-1 发动机的高温涡轮，在工程上单台发动机总寿命已安全运行达 10000h，现已证明：结构设计及改进是成功的；WJ5A-1 发动机的前二级燃气涡轮与压气机基本上是匹配的；燃气涡轮第一级导向器与动力涡轮导向器面积调整是合理的；在相对换算转速为 0.95 时，其喘振裕度与 WZ-5 发动机基本上一样；动力涡轮导向器面积总共放大了 5.32%，对燃气涡轮特性没有带来很大影响。

关键词： 高温涡轮 改装 串装 试验与分析

1 提高功率的方案

WZ-5 发动机航机陆用，由烧液体燃料改为烧天然气燃料，现已作中原油田气体处理增压部分的动力。在应用中存在的问题是：在高温大气条件下，动力装置的功率明显不足，经分析比较，用原 WJ5A-1 螺桨发动机的高温涡轮串装较合适。WJ5A-1 螺桨发动机是 WJ5 螺桨发动机的改型，对其三级定轴式燃气涡轮进行重新设计，第一级燃气涡轮工作叶片和导向叶片采用空心气冷，涡轮前最高燃气温度比 WJ5 发动机提高了 150℃，在使用中，实际上仅提高 120℃，燃烧室为适应热强度提高的需要，增加了冷却发散孔的数量，涡轮功的分配比例为：前二级燃气涡轮功占总功的 63.9%，与 WJ5 发动机相似，符合一般规律。WZ-5 发动机是 WJ-5 发动机的演变，在压气机燃烧室方面有其继承性，为适应 WZ-5 发动机改装原 WJ5A-1 发动机的高温涡轮，其燃烧室也增加了冷却发散孔的数量，只要 WZ-5 发动机作一些改进设计，改装原 WJ5A-1 发动机的高温涡轮是可能的，能确保该发动机在外界温度为 30℃海平面大气条件下，长时间地发出 1103kW。为了保证涡轮压气机合理地匹配，需在整机试车中对共同工作点作调整。涡轮与压气机共同工作方程式为：

$$(G_B \sqrt{T_1^*}/P_1^*) \cdot \sqrt{(\pi_k^{*(k-1)/k} - 1)/\eta_k^*} = A\pi_\alpha^* \qquad (1)$$

当 A 增加时，在同一换算转速下，增压比下降，空气流量增加，即共同工作线下移。在涡轴发动机中，常规、简单的办法是调整涡轮导向器面积。涡轮导向器处于临界时，涡轮导向器面积与 (1) 式中 A 的关系，通过燃气涡轮导向器和动力涡轮导向器的流量连续，可变换为：

$$A \propto F_{ca\,\mathrm{I}} \cdot \sqrt{1 - \{1/[(F_{ca\,\mathrm{III}}/F_{ca\,\mathrm{I}})C_1]^{(2n/n+1)\cdot(k_4 - 1/k_4)}\}} \qquad (2)$$

从上式看出，当动力涡轮导向器面积 $F_{ca\,\mathrm{III}}$ 增加时，A 要增加，如对 (2) 式取对数并微分，则可看出，燃气涡轮第一级导向器面积 $F_{ca\,\mathrm{I}}$ 增加时，A 也增加。在动力涡轮导向器处于临界，燃

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气涡轮导向器为高亚临界时，燃气涡轮膨胀比能够认为不变，当动力涡轮导向器 $\lambda_{ca\text{Ⅲ}}$ 从 1.0 降到 0.9 范围内时，影响燃气涡轮膨胀比值仅为 0.5%，可见用公式（2）来指导调整涡轮导向器面积还是很适用的。调整涡轮导向器面积 $F_{ca\text{Ⅰ}}$，$F_{ca\text{Ⅲ}}$ 的原则是充分发挥原 WJ5A-1 发动机高温涡轮作用，适当降低燃气发生器转速，保证必需输出轴功率、发动机喘振裕度以及必需的长寿命。

经分析计算，长期稳定工作的涡轮前燃气温度应不超过 1100K，根据原 WZ-5 发动机在中原油田与新疆克拉玛依现场运转的经验，燃气发生器相对转速定为 95% 左右较合适。

2 试验情况

为了摸索改装后的部件匹配，防止喘振，串装了一台 WJ5A-1 发动机高温涡轮后，将压气机放气活门一直打开进行整机试车，通过测试参数分析比较，证实了压气机与涡轮能协同工作，压气机放气活门如按原 WZ-5 发动机控制程序关闭，发动机不会进入喘振，但喘振裕度将大大减少。为了便于发动机参数调整，进行了正规程序的整机试车，结果见表 1。

表 1 整机试车结果

参 数	正规程序的摸底试车（t_H = 30℃，p_H = 101.3kPa）				涡轮导向器面积变化后试车（t_H = 20.5℃，p_H = 101.52kPa）			压气机零级导叶不可调时试车（t_H = 37℃，p_H = 100.13kPa）		
$\bar{n}_1$ (%)	92.5	95	97	95	90	95	97	90	95	97
$\bar{n}_2$ (%)	87.5	90.5	97.5	94	80	94	95	78.15	86.24	92.84
t_4 (℃)	490	525	540	520	450	495	500	470	498	506
N_B (kW)	917.5	1139.5	1337.4	1153.2	867.4	1406.6	1636.6	741.2	1107.4	1294.1
G_B (kg/s)					9.70	11.11	11.62	9.39	11.02	11.02
π_k^*		4.5	4.85	4.5	4.56	5.47	5.81	4.35	5.11	5.38

注：$\bar{n}_1$ 为燃气发生器相对转速，$\bar{n}_2$ 为动力涡轮相对转速，t_4 为动力涡轮出口温度，N_B 为输出轴功率 G_B 为进口空气流量，π_k^* 为压气机增压比

对表 1 数据进行验算，在 t_H = 15℃，p_H = 101.3kPa 时，燃气发生器相对转速为 95%，发动机喘振裕度仅为 5.46%，比原 WZ-5 发动机减少了 9.45%，见图 1 中 A 曲线。动力涡轮出口燃气温度，虽高于原 WZ-5 但未超过 WJ5A-1 的允许值。发动机输出轴功率达到了要求。

考虑油田的恶劣环境及发动机长期工作后喘振裕度变化，改装原 WJ5A-1 发动机的高温涡轮后，借助小偏差法调整了涡轮导向器面积 $F_{ca\text{Ⅰ}}$、$F_{ca\text{Ⅲ}}$，以便充分发挥高温涡轮的优势及保证与原 WZ-5 发动机的相同喘振裕度。根据原 WZ-5 部件特性及大量台架试验数据，建立了 WZ-5 定型发动机参数的互相影响，见表 2。曾应用在 WZ-5 发动机性能调试中，效果明显。

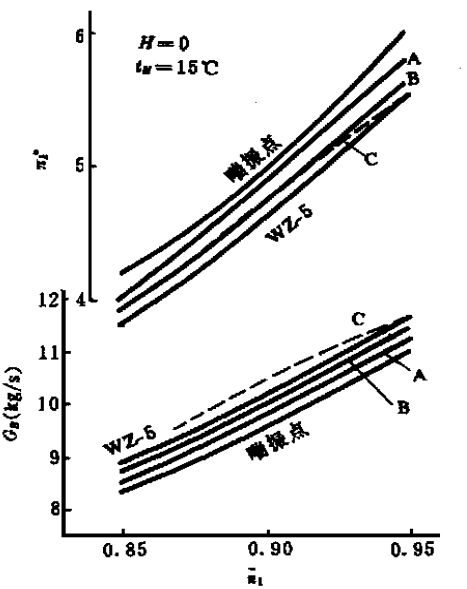

图 1 改装新、旧高温涡轮后，离喘振边界的裕度

表 2　WZ-5 定型发动机参数的互相影响

参　　数	燃导面积 $\delta F_{ca\,\mathrm{I}}$ 相对偏差	动导面积 $\delta F_{ca\,\mathrm{III}}$ 相对偏差	物理转速 δn 相对偏差	外界温度 δT_H 相对偏差
增压比相对偏差 $\delta\pi_k^*$	-0.367	-0.335	2.89	-1.445
空气流量相对偏差 δG_B	0.2145	0.1955	1.995	-1.498
燃气温度相对偏差 δT_4^*	0.84	-1.06	1.79	0.1
输出轴功率相对偏差 δN_B	2.294	-3.149	6.89	-2.945

WJ5A-1 发动机新、旧高温涡轮在涡轮导向器面积上略有变化，为了稳步前进，不急于一步到位，燃气涡轮第一级导向器面积放大 3.94%，动力涡轮导向器面积放大 2.76%，装配后进行整机试车，结果见表 1。通过这一调整，输出轴功率足以满足工程配套的需要，喘振裕度改善了，比改装原 WJ5A-1 发动机的旧高温涡轮增加了 5.95%，比原 WZ-5 发动机还少 3.5%，见图 1 中 B 曲线。由于燃气涡轮第一级导向器为焊接结构，对现存的，改变导向器通道面积有困难，为保证与 WZ-5 相同的喘振裕度，单独采用动力涡轮导向器面积放大，经用小偏差法进行分析计算，需放大 2.56%，该通过打磨动力涡轮导向器上、下圆板实现。WZ-5 发动机的压气机采用了零级导叶可调，在换算相对转速为 0.95 时，压气机零级导叶要复原，用于油田，简化了许多控制，去掉了压气机零级导叶可调，该改装的发动机，为模仿工程中实际情况，压气机零级导叶改为不可调，整机试车结果见表 1。将上述结果换算成标准情况，由图 1 中 C 曲线看出，在 $\bar{n}_1$= 0.95 时，其喘振裕度与 WZ-5 发动机基本上一样，在相对转速 0.95 以下，其喘振裕度要小，但足以满足油田总工程配套需要。

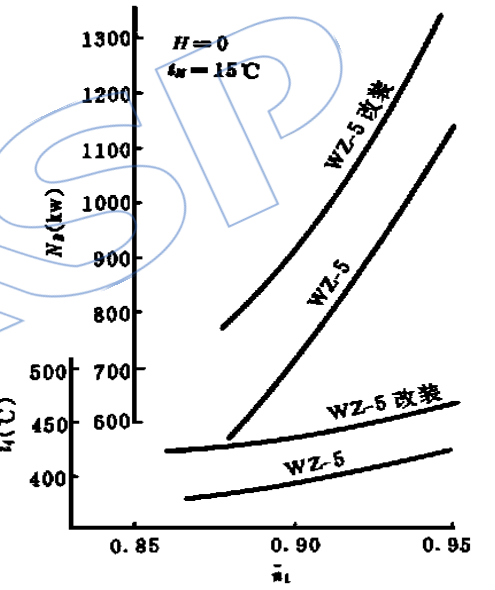

图 2　N_B、t_4 随 $\bar{n}_1$ 的变化

由图 2 可知，在 $\bar{n}_1$= 0.95 处，输出轴功率大约比原 WZ-5 增 220kW，解决了原 WZ-5 发动机作为油田气体处理增压部分动力的功率不足，动力涡轮出口温度比原 WZ-5 发动机增加 40℃，比原 WJ5A-1 发动机额定状态的规定值低，可见能足以保证发动机可靠地工作。

has obtained with the kerosene coolant through an even-heated straight tube, and relation between the heat transfer cooling of kerosene and water has been determined in the case of the vapor-liquid two-phase boiling flow. The key problem of the kerosene used as coolant is "coking property" and instability of wall temperature. However, it does happen in some particular working conditions, but the working conditions can be regulated with an empirical formula for the initial point annular flow Z_N to eliminate the coking zones. The Several useful conclusions have been drawn for the cooling passage of turbine vane.

STUDY ON FLOW CHARACTERISTICS OF SEPARATED IMPINGEMENT JETS AT SHORT DISTANCE

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ABSTRACT In conventional practice a row of separated circular jets is used in turbine blade or vane for impingement cooling and the relative distance z_n/d_n is very small ($z_n/d_n \leq 2$). In this case, study on longitudinal uniformity of the cooling on the surface of the blade or vane is necessary. In our experiments, the uniformity of the velocity distribution at large relative distance ($z_n/d_n > 10$) is achieved by free jet in atmosphere, but the distribution of jet velocity is rapidly uniformized when the jets srtike against the target surface and flow along the surface. The reason of the uniformization is the turbulence mixing and the effect of pressure difference. This work contributes to good understanding for uniformization of cooling on the surface of the blade or vane.

COMPARATIVE EXPERIMENTAL RESEARCH ON SPRAY FIELDS OF HEAVY AND CONVENTIONAL AVIATION KEROSENE

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ABSTRACT Laser holography was used to measure the fuel spray characteristics of heavy jet kerosene and conventional aviation kerosene downstream after a simple orifice injector. The spatial distribution of droplet size and Sauter Mean Diameters (SMD) for two kinds of kerosene have been obtained and compared. In this paper, the effects of air velocity and pressure drop on the fuel spray field are considered. The following conclusions are drawn from the experimental data: 1. The magnitude and distribution of droplet size are determined by the air velocity. 2. The SMD for the two fuels are, to some extent, related to the fuel pressure. 3. The variation of the fuel pressure has less influence on the SMD of the two fuels. 4. The empirical formulas are provided for evaluating the effects of the air velocity and the fuel pressure on the SMD.

RESEARCH ON WZ-5 TURBOSHAFT ENGINE WITH A REBUILT HIGH- TEMPERATURE TURBINE

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ABSTRACT A WZ-5 turboshaft engine has been modified with a rebuilt high-temperature turbine as a ground power plant. The engine can make full use of its turbine inlet temperature through varying areas of both gas generator turbine and power turbine nozzles and reduce the rotor speed, thus a sufficient surge margin is provided and the output shaft

power is enhanced. Therefore, the engine meets the requirements for long-time operation when it serves as a power plant in varied ground industrial complex. The practice of its usage has shown that the modified WZ-5 is of considerable economic and social benefits.

PRELIMINARY RESEARCH OF STEAM INJEETION FOR WZ-5 AEROENGINE COMBUSTOR

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ABSTRACT The experimental investigation has been carried out at atomospheric testing rig to determine the effect of steam injection on combustion performance. The combustor used in the experiment was a modified WZ-5 annular combustor in which two steam injection sets were installed in the front and rear parts respectively. The tested fuel was gaseous fuel with medium heating value. The results show that steam injection had no impact on combustion efficiency and exit temperature pattern when the mass injection ratio (steam mass flow rate/ air flow rate) is less than 5%. The exit temperature pattern factor increases and exceeds the acceptable value 0.25 to 0.30, as the steam mass injection ratio increases to about 10%. In addition, the test results also show that the process of the front part injection must be conducted smoothly, otherwise extinction of burning would occur.

EXPERIMENTAL INVISTIGATION OF LOW BTU COAL GAS COMBUSTION

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ABSTRACT Experimental investigation of an gas turbine combustor adapted to coal gas with heat value over 2500kJ/Nm^3 has been completed at all operation conditions. Test results show that the configuration of the chamber head with double swirlers provides high combustion efficiency and wide stable operation range when excess air coefficient of head (α_1) is in the range of 0.731 to 0.925. Carbon monoxide emission is confined within the required limits.

PREDICTION OF LNG DENSITIES WITH PRINCIPLE OF CORRESPONDING STATE OF SHAPE FACTOR

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ABSTRACT The principle of corresponding state of shape factor is applied to predicting the densities of LNG. For instance, methane is chosen as a reference fluid, high-precison equation of state and suitable binary interaction parameters are adopted. The comparison between calculations and experiments shows that the numerical results are in good agreement with the experimental data, so the method presented meets the requirements of the high-precision calculation for LNG densities, and it is also a success in prediction of thermal properties of cryogenic liquid mixtures with the principle of corresponding state of shape factor.