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蒸发式燃油喷射装置蒸发性能研究

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燃油在蒸发管内的蒸发，是一个复杂的过程，它受多种因素影响，例如燃油起始雾化平均滴径、与气流的相对速度、油气间的掺混、传热、传质、油蒸气的扩散、油雾在管内停留时间、管壁影响、气流温度、燃烧区传给它的热量，燃料的物理性能等等。燃料蒸发的理论研究多限于单滴油珠，因为油雾的计算极困难，因此要精确地进行理论计算目前还不可能。

目前的一些试验技术，包括取样分析，照相，收集蒸发的液相燃料称重计算，甚至激光测雾仪均难以探测直径大约 10μm 的小油滴[1,2]。但是从能量观点，即使直径小到几微米的油滴与油蒸气间仍然存在相变能-蒸发潜热。

本文力求抓住影响蒸发度的关键因素，从能量变化的角度进行工程应用计算。假定燃油喷入高温气流中后获得初始雾化，吸热升温，油滴表面达到某一平衡温度 T_s，在此平衡温度下吸收的热量作为相变热，已经汽化的燃油继续吸热升温和空气掺混，最后混合物以温度 T_e 排出蒸发管，并假定主要的汽化过程是在油滴表面平衡温度下完成的，即准稳态蒸发。由于在常用压力范围内蒸发性能对压力变化并不敏感或者随压力提高雾化蒸发性能有所改善[3]，本文计算时气流压力选为 500kPa，气流温度范围 200～600℃，蒸发管气油比范围为 1～8，包括了常用设计范围。

1. 燃油在蒸发管内的蒸发　已有研究证明，油滴在加热到表面平衡温度前的初始阶段蒸发很缓慢，因为到达油滴表面的热量大部分用于加热油滴。但该过程一旦完结就开始迅速蒸发，因为继续传来的热量仅有极小部分用于油核的升温，而大部分用作相变所需要的热量[4]。简化处理，本文不考虑起始升温阶段的蒸发量，因此列出能量守恒关系：

$$G_a(I_{ao} - I_{ae}) + Q = G_f \int_{T_{fo}}^{T_s} C_{pf}\,dT + VRG_fL + VRG_f \int_{T_s}^{T_e} C_{pfv}\,dT$$

或

$$AFR(I_{ao} - I_{ae}) + q = \int_{T_{fo}}^{T_s} C_{pf}\,dT + VRL + VR\int_{T_s}^{T_e} C_{pfv}\,dT \qquad (1)$$

式中 G_a 和 G_f 分别为空气和燃油的质量流量（kg/s）；I_{ao}和 I_{ae}分别为进、出口空气的焓（kJ/kg），Q 为蒸气管壁传热燃油的热量(kJ/s)，T_{fo}、T_e 和 T_s 为进口油温、油汽混合平衡温度和油滴蒸发时表面平衡温度，C_{pf} 和 C_{pfv} 是燃油和油蒸气的等压比热，$VR = G_{fv}/G_f$ 为蒸发度，L 为燃油蒸发潜热（kJ/kg），$AFR = G_a/G_f$ 为油气比。T_s 由以下关系式计算[3,5]：

$$P_m/P_{fs} - (M_f/M_a)L/[C_{pm}(T_m - T_s)] - 1 = 0 \qquad (2)$$

$$P_{fs} = eP\alpha[- b/(T_{cr} - T_{bn})]^{0.38} \qquad (3)$$

式中 P_m 和 P_{fs}是油气混合物压力和油滴表面饱合蒸气压力(kPa)，M_f 和 M_a 为油和空气的分

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子量，T_{cr}和 T_{bs}为燃油临界温度和正常平均沸点。对航空煤油取 $a=15.1962$，$b=4384.22$，T_s 的典型计算结果如图 1 所示。

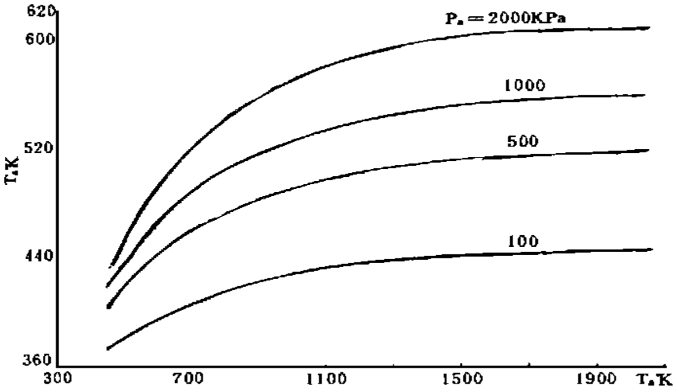

图 1　T_s 随 T_a 和 P_a 的变化

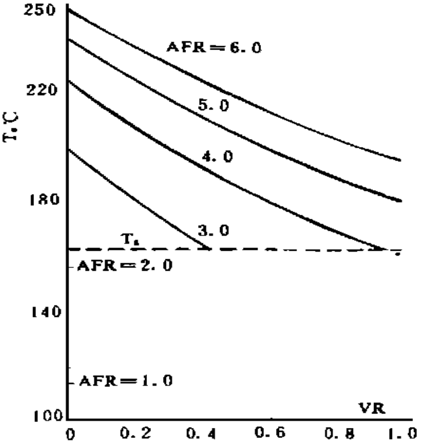

图 2　燃油在气流蒸发掺混后的 T_e

(1) 式中的 q 仅占燃油蒸发时吸收热量的小部分 (大约 20%)，计算时暂不考虑这部分热量 (在 4 中讨论)，当给定起始条件 T_{ao}，T_{fo}，AFR 等参数及有关燃料的热物性能后，就可计算出 T_e，VR 等参数。图 2 给出了 $T_a=400$℃，$I_{fo}=25$℃，$P_a=600$kPa 的一个算例。

如果测得混合物的平均温度 T_e 则可知燃油蒸发度 VR。但在实际的燃烧系统中 T_e 不易测知，为此引入最大蒸发度，即当 T_e 低于 T_s 时，认为已不可能存在显著的蒸发，将 $T_e=T_s$ 时达到的蒸发度称为最大蒸发度 VR_{max}。

2. 气流温度对最大蒸发度的影响　燃油在高温气流中蒸发所需的能量主要来自于气流，不同的气流温度下能获得的蒸发度是不同的。图 3 给出了在不同气油比下能获得的最大蒸发度与气流温度的关系。当气流温度不高时 (如 200℃)，在一般蒸发管内的气油比 (如 2～5) 状态下，燃油不可能获得显著的蒸发，只有改变蒸发管设计把气油比提高 (6.5～7.0 以上)，才能获得满意的蒸发。这是因为一般煤油型航空燃料的平均沸点或蒸发平衡温度大约在 140～210℃间，气流温度 200℃时没有太多的富裕热能供给燃油，仅能使燃油中低沸点组份蒸发。

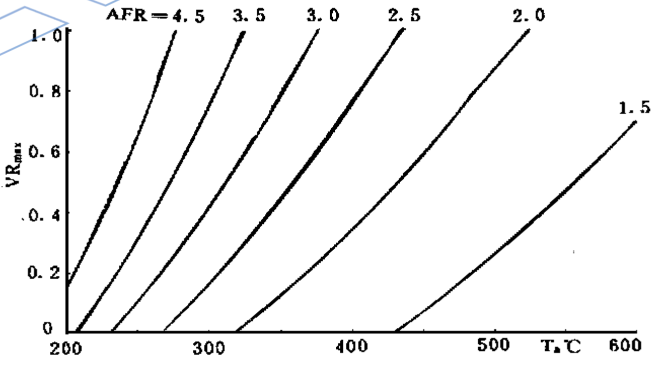

图 3　T_a 对 VR_{max} 的影响

3. 气油比对最大蒸发度的影响　设计蒸发管要考虑的一个最重要的问题是选择蒸发管内的气油比。图 4 给出了气油比与蒸发度的关系曲线。由图 4 可以看到二者大致成线性关系，且随着气流温度的增高，蒸发度对气油比越发敏感。但在所计算的进气范围内，若气油比小于 1，即使进气温度高达 600℃，燃油仍不可能获得明显蒸发。

4. 蒸发管壁传热影响　燃烧区传给蒸发管的热量很难直接测出，精确的计算也较困难，

多采用工程估算。本文依据实测的 T 型蒸发管在燃烧工况的壁温进行估算。计算结果表明，混气定性温度 T_m 的选取不会给传热的相对比较带来重大影响，因而可按 $T_m = 1/2\ (T_{a0} - T_e)$ 计算；一般情况下燃烧区传给蒸发管的热量仅占蒸发所吸收热量的 20% 以下，且 T_a 升高时这个比例更小，因此本文的近似处理不会带来重大偏差。同时根据燃烧区所传的热量对燃油在蒸发管内蒸发所作的贡献不大的判断，可以设想把传统的蒸发管概念引伸即把它从燃烧区挪出来成为一个独立的预混预蒸发装置，对于高压比发动机更便于设计，能获得理想性能。

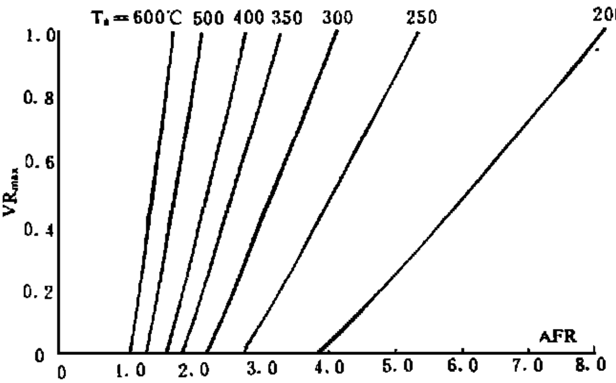

图 4　AFR 对 VR_{max} 的影响

5. 计算结果与试验结果比较　将本文计算结果与已进行过的蒸发管式短环型燃烧室试验结果进行对比分析：

对 Φ20–Φ8 蒸发管进行试验，进气量约为燃烧进气量的 7.3%，进气温度为 300℃。当 α= 3.35（AFR= 3.84），主燃区火焰黄色，但未伸出燃烧室。此时计算蒸发度约为 90%；当 α= 3 时，观察到燃烧室内偶尔有火焰闪动，显示有部分油珠燃烧，此时计算的蒸发度约 65%。

对 Φ22–Φ10 结构试验表明，当进气温度约 100℃，AFR= 5.83 时，主燃区火焰黄白色，闪动，可判断为油雾燃烧，此时计算蒸发度为 0，但由于蒸发管内气油比很大，气动雾化效果好，滴径不大，故火焰未伸出燃烧室外。保持气油比不变；进气温度升到约 300℃时，主燃区火焰变为蓝色泛黄，清晰，火焰不外伸，可判断为预混气燃烧，此时计算的蒸发度为 100%。当进气温度继续上升到约 450℃，燃烧现象及出口温场指标均同进气 300℃的情况，按计算它们都是完全蒸发的油与空气的混气燃烧。由上可见，定性对比计算结果与试验现象符合良好。

结论　(1) 为设计高效低污染清洁燃烧室，预混预蒸发的混气燃烧是可供选择的一种途径。(2) 蒸发管内燃油蒸发主要取决于气流所传递的能量，主燃区传热仅占小部分。对 T_a 高的燃烧室，蒸发管甚至无需浸没在主燃区，可以抽出演变成为其它结构型式的预混预蒸发装置。(3) 设计蒸发管或其它预混预蒸发装置，须根据燃烧室的 T_a 合理选择进气量，即达到最高的蒸发度，且节约用气。在保证燃油喷入预蒸发装置有足够的初雾化质量及足够的停留时间的前提下，对 T_a 约 200℃的装置需保证 AFR = 8 左右；T_a= 300℃，需使 AFR = 4；而 T_a 达到 500℃，可减少空气的用量，使 AFR = 2 就可获得满意的蒸发效果。但若把蒸发装置气油比设计成 1∶1 左右，即使进气温度高达 600℃也不可能获得明显的蒸发效果。(4) 预先计算 T_e 结合测量混合物温度，可给出一种符合定义的蒸发测量方法。

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TECHNICAL NOTES

CALCULATION FOR EVAPORATION OF AEROKEROSENE PROPLET

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ABSTRACT This paper discribes a new method for calculating the evaporation history of a droplet of multicomponent fuel. In this method kerosene is treated as a multicomponent fuel posed of ten fictitious components. The calculation is done by applying configuration of Kerosene Distillation. Also a new method is introduced to find the physical properties of the fictitious components. Finally, the methed is developed to calculate the evaporation history of a multicomponent liquid droplet by means of the evaporation equations. It is a more reliable and practical method than that used before. Some computational results are presented for three kinds of Chinese Aviation Kerosene, and compared to data obtained from our experiments favourably.

THE EFFECT OF SWIRLER ON SHORT REVERSAL-FLOW ANNULAR COMBUSTOR

Hong Yan (***Nanhua Powerplant Research Institute***)

ABSTRACT A short reversal-flow annular combustor has been tested with three different flame liner heads. The gas parameters of exit-section are detected by a turning measuring system, and data are processed by a PC-8001 microcomputer. Experimental results of efficiency, temperature field of exit-section, flame stabilization and pressure loss are presented. The effect of a swirler on the short reversal-flow annular combustor is illustrated by comparison and analysis. The experimental study shows that it is suitable to install a swirler on the flame liner head in a short reversal-flow annular combustor. This method can improve the combustor performance greatly. However, it should be noted that when a swirler is installed , its direction angle ought not to be too big, otherwise, as a result, carbon deposit will emerge, the swirler will give a negative effect on the combustor.

RESEARCH ON EVAPORATION PERFORMANCE FOR FUEL SPRAY VAPORIZER

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ABSTRACT A way to construct a clean combustor with high performance and low contamination is proposed by means of installation with beforehand mixing and evaporating. Direct measurement or accurate calculation of the evaporation rate in the evaporation installation is very difficult. According to energy relation, calculation is made based on the quasi-steady state evaporation model at the angle of engineering use. The concept of greatest evaporation rate of fuel in the evaporating installation is presented, and the effect of some primary factors is analysed. The calculated results are compared with test data.

A COMPUTATIONAL APPROACH TO THE LOADS SHARED BETWEEN THE TEETH OF TURBINE LUGS

Sheng Yuansheng (*Shenyang Institute of Aeronautical Engineering*)

ABSTRACT A displacement superposition method based on the principle of compatibility of deformation is approached for solving multi-contact problems. The formulas derived in this paper has been programmed to solve the load distribution between the teeth of a turbine disk lugs in association with FEM program, and then the maximum stress at each fillet of tooth is calculated. A study on fracture mechanics of the disk lug with different cracks in the tooth fillet is also presented. The results are in satisfactory agreement with data of the photoelastical experiments.

EXPERIMENTAL RESEARCH ON THE RESPONSE OF AN AXIAL COMPRESSOR TO INLET PERIODIC DYNAMIC DISTORTION

Feng Qi, Zhuang Huimin (*Nanjing Aeronautical Institute*)

ABSTRACT A pitot pressure pulsation generator and a data acquisition and processing system have been built up for this research. The response of a low pressure compressor to two kinds of inlet dynamic flow modes (axisymmetric or distorted) are investigated under the conditions of the compressor with or without a plenum. The results show that there is a sensitive frequency at which the perturbation is amplified through the compressor. The sensitive frequency is influenced not by inlet distortion, but by the plenum in the present research.

A DESIGN OF A TWIN VARIABLE CONTROL SYSTEM FOR AERO-TURBOJET ENGINE

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(*Northwestern Polytechnical University*)

ABSTRACT Under twin variable control with the equal low compressor speed and equal low turbine exit temperature, the twin spool turbojet can obtain higher power performance. In this paper, firstly, the engine dynamic model with two inputs and two outputs is deduced. Then with the aid of LQR theory, the optical regulator of twin variable control system is designed, and the approaches for processing some problems existed in the design process are recommanded. Finally, the control system designed in terms of optical method is simulated numerically. The results show that, in the condition of a state perturbantion on the system, the transient performance of the system recovered to original state is more satisfactory, and the variation of control mediators is in allowable limits of the controllers.