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氢在超音速气流中的燃烧过程*

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氢燃料超音速燃烧冲压发动机（简称“超燃冲压”）为主体的吸气式组合动力装置，已被证明是空天飞机推进器的最佳方案[1]。因而研究氢在超音速气流中的燃烧过程是一个重要的课题。国外近年来进行了大量的有关理论与实验研究工作[2,3]，但大多数的研究停留在氢处于静止与等压状态下的反应过程。在超燃燃烧室中的实际燃烧过程，由于不同的燃烧室进口气流状态，大体有以下三种基本类型：扩散型燃烧、扩散—动力型燃烧、动力型燃烧。许多文献指出，当进口空气静温与静压都很低时，化学反应进行得极慢，反应时间远远大于混合时间，可以近似认为氢与空气充分混合后燃烧，即动力型燃烧，燃烧速率取决于化学反应所需要的时间。燃烧室进口气流 Ma 越高（大致为飞行 Ma 的 1/3），混气停留在燃烧室内的时间越短。当飞行 Ma 很高时，混气可能在燃烧室内来不及反应，形成动力型的超燃冲压飞行极限。

本文详细研究了动力型燃烧过程、其气流参数的变化规律、以及影响着火时间和反应时间的各种因素。

1. 基本假设与计算的条件　模型燃烧室由等截面管与锥形管联接而成。为了达到超音速燃烧室的最佳设计性能，在不同的燃烧室进口 Ma 数下，需沿轴向位置调节燃料喷射位置[4]。假设在燃烧室 $O-O$ 截面处，氢气和空气已混合均匀，反应呈动力型燃烧状态。不同进口 Ma 数下，设燃烧室尺寸分别为：$Ma=2.7$ 时，$L'=15$cm；$Ma=3.3$，$L'=30$cm；$Ma=4.0$，$L'=45$cm；$Ma=5.0$，$L'=60$cm。其中 L' 是从 $O-O$ 截面开始计算的等截面管长度，燃烧室总长 200cm，锥形扩张角 1.5°。飞行 Ma 数 6~15，进口静压 $P_o=10\sim50$kPa，进口静温 $T_o=900\sim2100$K，当量油气比 $\varphi=1.0$。文献[3]的计算已证明，当量油气比 φ 在 0.5~1.7 之间，着火时间与反应时间几乎与当量油气比 φ 无关，因此当量油气比 $\varphi=1$ 的计算结果能说明超燃燃烧室在该工作范围内的普遍性能。

参加反应的 12 个组分有：H、O、OH、H_2、O_2、H_2O、HO_2、H_2O_2、N、NO、NO_2、N_2。列出了 31 个化学反应式。采用 Tyson. J 的隐式积分法，在文献[5]的计算机程序基础上作了部份改进。

2. 计算结果分析与讨论　图 1 中曲线变化说明了 Ma 数对燃烧室内反应过程的影响。燃烧室进口 Ma 数越高，气流速度越大，混气在燃烧室内停留的时间越短，混气来不及反应，因此燃烧室出口截面温度越低。同图还给出沿燃烧室轴线坐标 x 与时间 τ 的关系曲线。

比较图 2a 和 b 可见（a 和 b 进口静温 T_o 分别为 1300K 和 2100K），在燃烧室出口截面处，O_2 和 H_2 的浓度在不断降低，说明混气在燃烧室内还未完全燃烧。这证明，即使进口静

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温很高（如 T_o= 2100K），由于进口 Ma 很高，混气在燃烧室内停留时间短，导致燃烧室性能恶化。

图 3 所示为进口静压 P_o 对燃烧室内燃烧过程的影响（Ma= 3.3，T_o= 1100K，φ= 1）。P_o= 50kPa 时，在 x= 100cm 处（从 $O-O$ 截面算起）温度达到最大值（OH 基浓度在 x= 150cm 处达到最大值），说明放热过程基本上结束。在 x> 100cm 后静温降低是因为此时放热速度缓慢，管道扩张使静温降低。P_o= 20kPa 时，着火点离 $O-O$ 截面约 100cm。而 P_o= 10kPa 时，混气在燃烧室内来不及着火，构成超音速燃烧室的动力型燃烧性能极限。

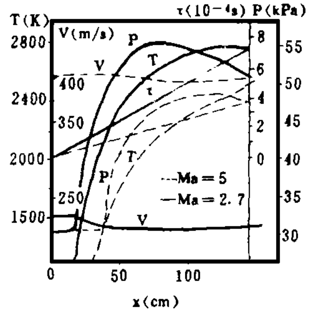
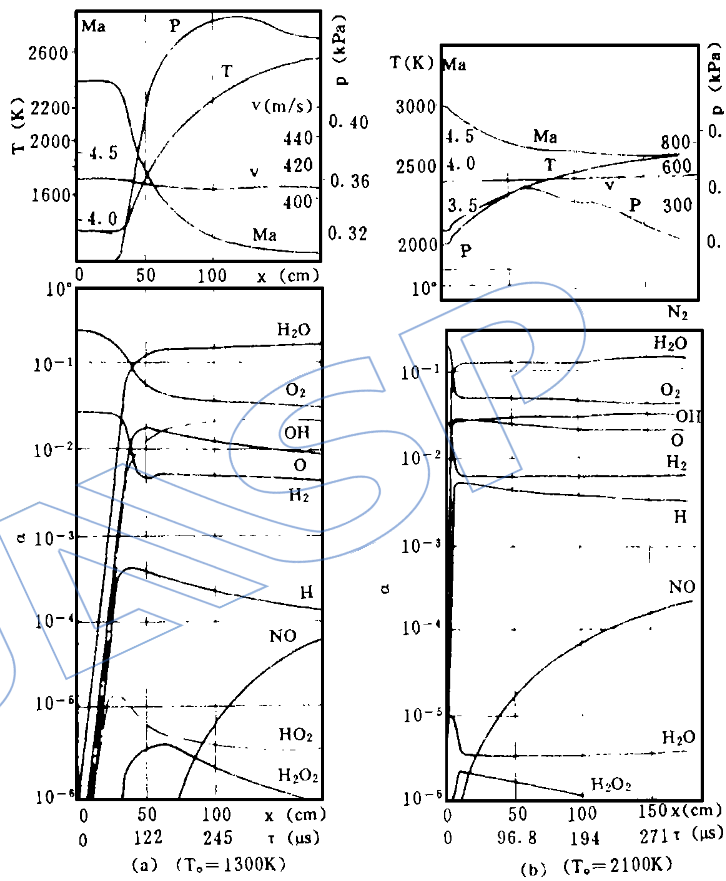


图 1 进气流 Ma 数的影响



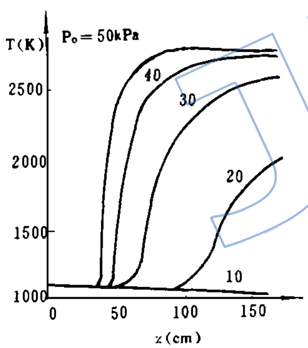


图 3 进口静压的影响

图 2 组分与气流参数的变化（Ma= 5.0，φ= 1，P_o= 0.3× 10^5Pa）

本文基于燃烧室进口静温和静压很低时，燃烧室内混气呈动力型燃烧，通过计算进一步分析了当超燃冲压飞行 Ma 数不断向更高速度发展时，将出现超燃冲压动力型燃烧飞行极限。提供了超燃冲压性能设计的重要依据。

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the references for searching the eigenvalues are the first k-th powers of the eigen determinants (where k is larger than 1.0) instead of the determinants themselves, and the searching formulas of the existing method are modified correspondingly. As the range of the references for searching the eigenvalues is reduced considerably, the phenomenon of numerical overflow is eliminated forever.

J- INTEGRAL FOR 2-D VARIABLE- THICKNESS PLATE

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ABSTRACT The formula of a J-integral presented by J. R. Rice is extended to problem of 2-D variable-thickness plates. The extended J-integral formula is derived in terms of the path independent. Then the integral conservation is verified by using finite element method. At last, the calculation results for some variable thickness plates made of photoelastic material are compared with their photoelastic test data, and the differences between them are less than 4%. It is proved that the extended J-integral formula for the 2-D variable-thickness plates is path independent and can be taken as a fracture paramarater for damage tolerance analysis. Furtheremore, this integral can be solved numerically by using 2-D general finite element programs. It is therefore of practical value for the fracture analysis of Ⅰ mode cracked plate with thickness which does not vary too mueh.

COMBUSTION PROCESSES OF HYDROGEN IN A SUPERSONIC AIR FLOW

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ABSTRACT According to the implicit numerical integration method proposed by Tyson. J, an improved computer program for pseudo-one-dimensional flow of combustion kinetics is developed with the aid of a chemical kinectic model with 12-species and 31 reaction. Variations of temperature, prssure, Mach number and mass fraction of chemical species in a supersonic combustion model are studied in detail. The results of scramjet combustor conditions corresponding to flight Mach numbers 6, 10 and 15 show that chemical reaction rates decrease at rather low temperature and pressure at a combustor inlet and there is not enough time to ignite the mixture-gas in the combustor at very high Mach number, in result the performance limits of scramjet kinetic combustion occur.

CHARACTERISTICS OF DUAL SWIRLERS SPRAYER DEVICE

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ABSTRACT The spray characteristics of dual radial swirlers mixing-cup sprayer device have been investigated with the aid of Malvern laser granulometer and checked the differences of its spray characteristics from those of the pressure atomizing fuel nozzle. Two air flow proportions of the first swirler to the second one are 50%∶50% and 30%∶70%. The airflow velocity at the exit-section has been designed in the range 37 to 74m/s. In the tests the fuel pressure ranges from 2.94 to 4.41×10^5Pa. The test results show that in the case of reasonable design, the sprayer device is able to provide better spray characteristics than pressure atomizing fuel nozzle.