

论冷效模拟实验的模拟理论

北京航空航天大学 邱绪光^{**}

【摘要】 从所需微分方程组及单值性条件出发, 以严格的相似理论得出涡轮叶片冷效模拟实验所应遵循的模化条件。指出, 当实验所用压力比原型低的条件下, 为满足表征密流水平的准则 pL/μ $\overline{c_p T}$ 相等的条件, 则实验所用温度水平也应下降。为能模拟高增压比发动机高压涡轮叶片的冷效, 应尽可能提高实验器的压力水平并适当地降低实验中的温度水平, 不应采取与此相反措施。

关键词: 相似 涡轮叶片 冷效模拟 实验

我国有关单位对冷却涡轮叶片进行冷效实验的方法基本上是结构比较性实验方法。

本文作者曾用量纲分析法(“灰箱法”)分析了涡轮冷效模拟实验^[1], 但未考虑涡轮叶片材料及尺寸问题, 且“灰箱法”更多地取决于经验知识。因此, 本文拟用方程分析法对所涉课题作更详细、具体的论证, 目的在于揭示模拟。

1 现象总体性质及燃气侧叶栅理想流分析

如暂不计及气膜冷却而只认对流冷却, 则整个现象可看成是两面以第三类边界条件耦合的导热问题, 其特殊性在于: 两边的换热系数 α_c 和 α 、温度 T_g 和 T_c 不仅处处不同, 且只能以解两边的换热问题来间接给定。也可把现象整体看成是两边热边界条件互耦的对流换热课题。当解两边任一边的对流换热课题时, 壁面热边界条件($T_{w.g}$ 、 $T_{w.c}$ 或 q_w 等)无法简单给定、而是以另一面的对流换热结果来耦合, 间接给定。另外, 对燃气侧的问题, 因有附面层理论可用, 因此, 把对叶栅的分析和对叶片的分析分开, 把“尺度效应”(和粘性及导热性联系)限于单个叶片, 而不是整个叶栅。

对燃气侧叶栅流动做理想(无粘、无导热)流分析的目的在于得出燃气侧附面层流动与换热课题所需的层外基流参数, 它是理想流问题中的叶片表面的有关参数分布, 例如 u_s 、 T_s 、 p_s (表面上的 s 向分速 u_s 、温度 T_s 及压力 p_s)的面分布。

叶栅理想流适用微分方程组为:

$$\begin{aligned}(\rho v_i) / \partial x_i &= 0, \quad v_j (\partial v_i / \partial x_j) = - (1/\rho) (\partial p / \partial x_i) \\ v_i (\partial T / \partial x_i) &= (1/\rho c_p) v_i (\partial p / \partial x_i), \quad p = \rho R T\end{aligned} \quad (1)$$

其适用单值条件为: 叶栅前 $p_{g,1}$ = 常量, $T_{g,1}$ = 常量, $c_{p,g,1}$ = 常量, $u_{g,1}$ = 常量

叶栅后 $p_{g,2}$ = 常量

如果温度 $T_{g,1}$ 沿叶高 z 向呈某种分布函数 $T_{g,1} = T_{g,1}(z)$ 时, 这意味着其相对型 $\bar{T}_{g,1} = \bar{T}_{g,1}(\bar{z})$ 在模型上与原型上应相同, 即所谓单值条件相似, 其它单值条件类此处理。

以 l 度 x_i (或 x_j), 以 v_0 度 v_i (或 v_j), 以 p_0 度 p , 以 ρ_0 度 ρ , 以 c_{p0} 度 c_p , 可得未具体规定度量单位大小的第二相对型 (按 П. К. Кочетков 的说法) 方程组及单值条件为:

$$\frac{\partial \bar{p}_{v_i}}{\partial \bar{x}_i} = 0, \quad \bar{v}_j \frac{\partial \bar{v}_i}{\partial \bar{x}_j} = -\frac{p_0}{\rho_0 v_0^2} \frac{1}{\bar{p}} \frac{\partial \bar{p}}{\partial \bar{x}_i}, \quad \bar{v}_i \frac{\partial \bar{T}}{\partial \bar{x}_i} = \frac{p_0}{\rho_0 c_{p0} T_0} \frac{1}{\bar{p} \bar{v}_i} \frac{\partial \bar{p}}{\partial \bar{x}_i}, \quad \bar{p} = \frac{\rho_0 R_0 T_0}{p_0} \bar{p} R T \quad (2)$$

式中 $p_0/\rho_0 v_0^2, p_0/\rho_0 c_{p0} T_0, \rho_0 R_0 T_0/p_0$ 等, 构成单位选择约束条件。选定叶栅某特征尺度 l 以及 $u_{g,1}, p_{g,1}, T_{g,1}$ 为基本测量单位。

在服从高斯单位选择规则的条件下, (2) 式及相应的单值性条件变为:

$$\frac{\partial (\bar{p}^{(k)} \bar{v}_i)}{\partial \bar{x}} = 0, \quad \bar{v}_j \frac{\partial \bar{v}_i}{\partial \bar{x}_j} = -\frac{1}{\bar{p}^{(k)}} \frac{\partial \bar{p}}{\partial \bar{x}_i}, \quad \bar{v}_j \frac{\partial \bar{T}_i}{\partial \bar{x}_i} = \frac{1}{\bar{p}^{(k)} \bar{v}_i} \frac{\partial \bar{p}}{\partial \bar{x}_i}, \quad \bar{p} = \bar{p}^{(k)} R^{(k)} T \quad (3)$$

叶栅前: $T_{g,1} = 1, \quad \bar{p}_{g,1} = 1, \quad \bar{c}_{g,1}^{(k)} = c_{pg,1} T_{g,1} / u_{g,1}^2 = \text{常数}, \quad \bar{u}_{g,1} = 1$

叶栅后: $p_{g,2}/p_{g,1} = \bar{p}_{g,2} = \text{常数}, \quad R^{(k)} = R T_{g,1} / u_{g,1}^2 = \text{常数}$

(3) 式在数学结构上同于 (1) 式, 在遵守高斯单位选择规则的条件下 (3) 式与 (2) 式是全同式。据相似第二定理, 从 (3) 式及单值条件式可以就各未知函数写出其解式如下:

$$\bar{v}_i = \frac{v_i}{u_{g,1}} = f_1 \left[\frac{p_{g,2}}{p_{g,1}}, \frac{u_{g,1}}{k R T_{g,1}}, k; \frac{x_i}{l} \right], \quad \bar{p} = \frac{p}{p_{g,1}} = f_2 \left[\frac{p_{g,2}}{p_{g,1}}, \frac{u_{g,1}}{k R T_{g,1}}, k; \frac{x_i}{l} \right]$$

$$T = \frac{T}{T_{g,1}} = f_3 \left[\frac{p_{g,2}}{p_{g,1}}, \frac{u_{g,1}}{k R T_{g,1}}, k; \frac{x_i}{l} \right], \quad \bar{p}^{(k)} = \frac{\rho u_{g,1}^2}{p_{g,1}} = f_4 \left[\frac{p_{g,2}}{p_{g,1}}, \frac{u_{g,1}}{k R T_{g,1}}, k; \frac{x_i}{l} \right] \quad (4)$$

k 为栅前气流之比热比, 在很多情况 (包括我们的研究对象) 下 k 变化很小, 可从 (4) 式中去掉。

(4) 式表明, 定型准则无包含尺度 l 之准则, 因此, 模型的尺寸是自由的。这是重要结论。

2 燃气侧对流换热分析

对燃气侧换热, 无论叶盆或叶背, 适用附面层理论。所适用微分方程组及单值性条件为:

连续
$$\frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho v)}{\partial y} = 0$$

动量
$$u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = u_s \frac{\partial u_s}{\partial x} + v_s \frac{\partial^2 u}{\partial y^2}$$

能量
$$u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = a_g \frac{\partial^2 T}{\partial y^2} + \frac{v}{c_{p,g}} \left(\frac{\partial u}{\partial y} \right)^2$$

换热
$$\alpha_{g,s} (T_{g,1} - T_{w,g}) = -\lambda_g \left(\frac{\partial T}{\partial y} \right)_{s,n=0} = q_{w,s}$$

冷效
$$\eta_l = \frac{T_{g,1} - T_{w,g}}{T_{g,1} - T_{c,1}} = \left[1 + \frac{\alpha_{c,s}}{\alpha_{g,s}} + \frac{\alpha_g \delta}{x_m} \right]^{-1} \quad (5)$$

上式中使用曲线坐标系, s 标沿叶面弧线, 其 0 点应为前驻点 (某被模拟工况下理想流 λ 流线, 它随工况变化), s 称 “进展度”, 表征粘性、导热性扰动扩散发展程度。

除密度外, 假设运动粘性 ν 、导热系数 λ 、比热 c_p 等为场常量。先解附面层内速度分布等力学课题, 再解能量交换换热课题。在解附面层课题时, 附面层外速度 u_s 、温度 T_s 及压力 p_s 等皆属已知, 由解叶栅理想流之结果 (4) 式给定。但叶片燃气侧表面热边界条件应由冷气端换热结果来决定。因此, 这个热边界条件应由可决定冷端所需单值性条件来构成。依据经验应该是:

冷气入口: $p_{c,1} = \text{常量}, T_{c,1} = \text{常量}, \nu_{c,1} = \text{常量}, a_{c,1} = \text{常量}, c_{p,c,1} = \text{常量}, \lambda_{c,1} = \text{常量}, u_{c,1} = \text{常量}$

由于燃气侧热边界条件是由冷气端冷气对壁面 (其冷端为 $T_{w,c}$) 换热给定的, 因此应同时给定壁材料导热特征条件: $\lambda_m / \delta = \text{常量}$ (或 $\lambda_m = \text{常量}$ 与 $\delta = \text{常量}$)

方程组 (5) 及后述单值条件之第二相对型为

连续
$$\frac{\partial \bar{p}_u}{\partial s} + \frac{v_{0s0}}{u_{0y0}} \frac{\partial \bar{p}_u}{\partial y} = 0$$

动量
$$\bar{u} \frac{\partial \bar{u}}{\partial s} + \frac{v_{0s0}}{u_{0y0}} \bar{v} \frac{\partial \bar{u}}{\partial y} = \frac{u_{s0}^2}{u_0^2} \bar{u}_s \frac{\partial \bar{u}_s}{\partial s} + \frac{v_{0s0}}{u_{0y0}^2} \bar{v} \frac{\partial^2 \bar{u}}{\partial y^2}$$

能量
$$\bar{u} \frac{\partial \bar{T}}{\partial s} + \frac{v_{0s0}}{u_{0y0}} \bar{v} \frac{\partial \bar{T}}{\partial y} = \frac{a_{0s0}}{u_{0y0}^2} \bar{a} \frac{\partial^2 \bar{T}}{\partial y^2} + \frac{v_{0s0} u_0}{c_{p0} T_{0y0}^2} \frac{\bar{v}}{\bar{c}_p \cdot g} \left(\frac{\partial \bar{u}}{\partial y} \right)^2$$

换热
$$\bar{\alpha}_{g,s} (\bar{T}_{g,1} - \bar{T}_{w,g}) = - \frac{\lambda_{g0}}{\alpha_{g0} y_0} \bar{\lambda}_g \left(\frac{\partial \bar{T}}{\partial y} \right)_{\bar{s}, \bar{n}=0}$$

冷效
$$\eta_1 = \frac{T_{g,1} - T_{w,g}}{T_{g,1} - T_{c,1}} = \left[1 + \frac{\alpha_g}{\alpha} + \frac{\alpha_g \delta}{x_m} \right]^{-1} \quad (6)$$

今选定 $s, u_s, v_{g,1}, p_{g,1}$ 及 $T_{g,1}$ 为基本测量单位。由约束条件得 $u_{s,0} = u_0 = u_s, y_0^{(k)} = v_{0s0}/u_0 = v_{g,1}s/u_s, v_0^{(k)} = u_{0y0}/s_0 = u_s v_{g,1}/s, a_0^{(k)} = v_0 = v_{g,1}, c_{p0}^{(k)} = u_s^2/T_{g,1}, \alpha_{g0}^{(k)} = \lambda_{g0}/y_0 = \lambda_{g0}s/y_{0s0}$ 。于是(6)式及相应的单值条件现可改写成:

$$\left. \begin{aligned} \frac{\partial \bar{p}_u}{\partial s} + \frac{\partial \bar{p}_u}{\partial y^{(k)}} &= 0, \quad \bar{u} \frac{\partial \bar{u}}{\partial s} + \bar{v}^{(k)} \frac{\partial \bar{u}}{\partial y^{(k)}} = \bar{u}_s \frac{\partial \bar{u}_s}{\partial s} + \bar{v} \frac{\partial^2 \bar{u}}{\partial y^{(k)2}} \\ \bar{u} \frac{\partial \bar{T}}{\partial s} + \bar{v}^{(k)} \frac{\partial \bar{T}}{\partial y^{(k)}} &= \bar{a}^{(k)} \frac{\partial^2 \bar{T}}{\partial y^{(k)2}} + \frac{\bar{v}}{\bar{c}_p} \left(\frac{\partial \bar{u}}{\partial y^{(k)}} \right)^2, \quad \bar{\alpha}_g^{(k)} (\bar{T}_{g,1} - \bar{T}_{w,g}) = - \bar{\lambda}_g \left(\frac{\partial \bar{T}}{\partial y^{(k)}} \right)_{\bar{s}, \bar{n}=0} \\ \eta_1 &= \frac{T_{g,1} - T_{w,g}}{T_{g,1} - T_{c,1}} = \left[1 + \frac{\alpha_g}{\alpha} + \frac{\alpha_g \delta}{x_m} \right]^{-1} \end{aligned} \right\} \quad (7)$$

相应的热边界条件应为:

冷气入口端: $\frac{p_{c,1}}{p_{g,1}} = \text{常数}, \frac{T_{c,1}}{T_{g,1}} = \text{常数}, \frac{v_{c,1}}{v_{g,1}} = \text{常数}, \frac{a_{c,1}}{v_{g,1}} = \text{常数}, \frac{\lambda_{c,1}}{\lambda_{g,1}} = \text{常数}, \frac{c_{p,1} T_{g,1}}{u_g} = \text{常数}$

叶片壁面条件: $\lambda_w T_{g,1}/p_{g,1} u_s \delta = \text{常数}$

现根据相似第二定理且仅就冷效一个未知函数写出其解式如下:

$$\eta_1 = f_1 \left[\bar{u}_s, \bar{v}, \bar{c}_p^{(k)}, \bar{a}^{(k)}; \frac{p_{c,1}}{p_{g,1}}, \frac{T_{c,1}}{T_{g,1}}, \frac{v_{c,1}}{v_{g,1}}, \frac{a_{c,1}}{v_{g,1}}, \frac{\lambda_{c,1}}{\lambda_{g,1}}, \frac{c_{p,1} T_{g,1}}{u_s^2}, \frac{u_{c,1}}{u}, \frac{\lambda_w T_{g,1}}{p_{g,1} u_s \delta}, \frac{y_0}{s} \equiv \frac{v_{g,1}}{u_s s} \right] \quad (8)$$

依据(4)式, $\bar{u}_s = \frac{u_s}{u_{g,1}}$ 是 $\frac{p_{g,2}}{p_{g,1}}, \frac{u_{g,1}}{kRT_{g,1}}, k$ 的函数, 因此应有(合并):

$$\eta_1 = f_2 \left[\frac{p_{g,2}}{p_{g,1}}, \frac{u_{g,1}}{kRT_{g,1}}, k, \frac{a_{c,1}}{v_{g,1}}, \frac{p_{c,1}}{p_{g,1}}, \frac{T_{c,1}}{T_{g,1}}, \frac{v_{c,1}}{v_{g,1}}, \frac{a_{c,1}}{v_{g,1}}, \frac{\lambda_{c,1}}{\lambda_{g,1}}, \frac{c_{p,1} T_{g,1}}{u_{g,1}^2}, \frac{u_{c,1}}{u_{g,1}}, \frac{\lambda_w T_{g,1}}{p_{g,1} u_{g,1} \delta}, \frac{u_{g,1}s}{v_{g,1}}, \frac{s}{l} \right] \quad (8')$$

在一切含 u_s 的复合量中 u_s 均被 $u_{g,1}$ 取代, 例如, $c_{p,1} T_{g,1}/u_s^2 \equiv c_{p,1} T_{g,1}/u_{g,1}^2 = (u_{g,1}/u_s)^2$, 而由于 $u_s/u_{g,1}$ 本身是 $p_{g,2}/p_{g,1}, c_{p,1} T_{g,1}/u_{g,1}$ 及 k 的函数, 故有理由将 $c_{p,1} T_{g,1}/u_s^2$ 改写为 $c_{p,1} T_{g,1}/u_{g,1}^2$ 。另外, 在测量尺度比例 $p_{c,1}/p_{g,1}, T_{c,1}/T_{g,1}, u_{c,1}/u_{g,1}, v_{c,1}/v_{g,1}, s/l$ 皆保存的条件下, 有理由把 $c_{p,1} T_{g,1}/u_{g,1}^2, a_{c,1}/v_{g,1}$ 等改写成 $a_{c,1}/v_{c,1}$ 及 $c_{p,1} T_{c,1}/u_{c,1}^2$ 等。于是(8')式可改写成:

$$\eta_1 = f_3 \left[\frac{p_{g,2}}{p_{g,1}}, \frac{u_{g,1}}{kRT_{g,1}}, k, Pr_{g,1}, \frac{p_{c,1}}{p_{g,1}}, \frac{T_{c,1}}{T_{g,1}}, \frac{\lambda_{c,1}}{\lambda_{g,1}}, \frac{c_{p,1} T_{g,1}}{u_{g,1}^2}, \frac{u_{c,1}s}{v_{g,1}}, \frac{u_{c,1}}{u_{g,1}}, Pr_{c,1}, \frac{\lambda_w T_{g,1}}{p_{g,1} u_{g,1} \delta}, \frac{v_{c,1}}{v_{g,1}}, \frac{s}{l} \right] \quad (8'')$$

由于冷气端换热分析无基流与附面层之分, 其长度尺度只能用叶片本身尺度, 因此, 在保留单个叶片全几何相似的条件下, 除保留 s/l (其中 l 为单个叶片特征尺度) 作为说明 $T_{w,g}$ 是沿叶面的分布函数外, $u_{g,1}s/v_{g,1}$ 可写成 $u_{g,1}l/v_{c,1}$, $\lambda_w T_{g,1}/p_{g,1} u_{g,1} \delta$ 可改写成 $\lambda_w T_{g,1}/p_{g,1} u_{g,1} l$ 。再者, 在冷气端粘性推及全区而不像燃气端粘性仅作垂直向传播 (v_g 的量纲为 l^2/τ) 且限于一个薄层所谓附面层内, 而在给气端, 全方位扩散性及其影响的全区性, v_c 已失去作为基本单位的资格, 它是导得单位, $v_{c,0} = u_{g,1}l$, 从而应有 $v_{c,1} = v_{c,1}/u_{g,1}l = (v_{c,1}/u_{c,1}l) \cdot (u_{c,1}/u_{g,1})$, 由于 $u_{c,1}/u_{g,1}$ 已在解式中作为独立自变量出现, 作为隐函解式, 可只取 $v_{c,1}/u_{c,1}l$ 取代之。于是可把(8'')式写成:

$$\eta_1 = f^4 \left(\frac{p_{g,2}}{p_{g,1}}, \frac{p_{c,1}}{p_{g,1}}, \frac{T_{c,1}}{T_{g,1}}, \frac{u_{g,1}^2}{kRT_{g,1}}, \frac{u_{g,1}l}{v_{g,1}}, Pr_{g,1}, \frac{\lambda_{c,1}}{\lambda_{g,1}}, k_{g,1}, \frac{c_{pc,1}T_{c,1}}{u_{c,1}^2}, \frac{u_{c,1}l}{v_{c,1}}, \frac{u_{c,1}}{u_{g,1}}, \frac{\lambda_m T_{g,1}}{p_{g,1}u_{g,1}l}, \frac{s}{l} \right) \quad (9)$$

(8)式至(9)只做了概念上的调整未对复合自变量舍弃或省略处理,是一个完整理论式。

$Pr_{c,1}$ 和 $Pr_{g,1}$ 的具体数学结构将是 $(Pr_{c,1}/Pr_{g,1})^n$, $Pr_{c,1}$ 和 $Pr_{g,1}$ 在很大的温度范围内变化很小(前者在0.703附近,后者在0.72附近作微小变化,且 n 为0.33左右),因此可望在原型及模型所涉温度范围内 $(Pr_{c,1}/Pr_{g,1})^n$ 变化极微而会“自动相等”,从而把 $Pr_{c,1}$ 和 $Pr_{g,1}$ 皆行略去。

另外,尽管皆属可压流,但叶栅的流动情况大大地不同于无限空间绕流机翼之类的课题。考察其基流,从力学角度看,压变大、动量变化大,从能量角度看,总能及总温不变但静焓和动能之间的转化大。即附面层外之 u_s 、 T_s 及 ρ_s 变化极大。栅前初动量及初动能反而很小。对流换热的强度主要取决于密流 $\rho_s u_s$,因此,附面层课题中当地雷诺数 $Re_s = \rho_s u_s / \mu_s$,在忽略初速 $u_{g,1}$ 之后,按一维流或某任一流股来说密流 $\rho_s u_s$ 有:

$$\rho_s u_s = \rho_1 \left(\frac{p_s}{p_1} \right)^{\frac{1}{k}} \cdot \sqrt{2 \frac{k}{k-1} \frac{p_1}{\rho_1} \left[1 - \left(\frac{p_s}{p_1} \right)^{\frac{k-1}{k}} \right]} = \frac{p_1}{RT_1} \cdot f \left(k, \frac{p_s}{p_1} \right) \quad (10)$$

在存在几何相似又规定了最终的 $p_{g,2}/p_{g,1}$ 之后, p_s/p_1 分布(沿叶面)现在只取决于 p_1/RT_1 ,所以,可以把 $\rho_s u_s / \mu_s$ 写成 $p_1 s / (\mu_s RT_{g,1})$,而在 μ_s 为场常量的假设及燃气端和冷气端统一尺度(决定取单个叶片的全几何相似) l 及已把 s/l 当为自变量等条件,可把燃气端 $p_{g,1} s / (\mu_s RT_{g,1})$ 写成 $p_{g,1} s / (\mu_s RT_{g,1}) \equiv (p_{g,1} l / \mu_{g,1} c_{pg,1} T_{g,1}) / [k/(k-1)]^{1/2}$,考虑到(10)式中有因子 $k/(k-1)$,从而可把上述 Re_s 改写成 $(k/k-1)(p_{g,1} l / \mu_{g,1} c_{pg,1} T_{g,1})$ 。根据类似的理由可把冷气端的雷诺数也改写成 $(p_{c,1} l / \mu_{c,1} c_{pc,1} T_{c,1}) / [k/(k-1)]$ 。与此同时,略去燃气端及冷气端的 $c_p T / u^2$ (具体为 $c_{pg,1} T_{g,1} / u_{g,1}^2$ 及 $c_{pg,1} T_{c,1} / u_{c,1}^2$)。这时可把(9)式改写成:

$$\eta_1 \equiv \frac{T_{g,1} - T_{w,g}(s)}{T_{g,1} - T_{c,1}} = f \left(\frac{p_{g,2}}{p_{g,1}}, \frac{T_{c,1}}{T_{g,1}}, \frac{p_{c,1}}{p_{g,1}}, \frac{k}{k-1}, \frac{p_{g,1} l}{\mu_{g,1} c_{pg,1} T_{g,1}}, \frac{\lambda_{c,1}}{\lambda_{g,1}}, \frac{k}{k-1}, \frac{p_{c,1} l}{\mu_{c,1} c_{pc,1} T_{c,1}}, \frac{\lambda_m T_{g,1}}{p_{g,1} u_{g,1} l}, \frac{s}{l} \right) \quad (11)$$

对于以冷气方壁温 $T_{w,c}$ 为基的冷效式也可写成:

$$\eta_1 = f \left(\frac{p_{g,2}}{p_{g,1}}, \frac{T_{c,1}}{T_{g,1}}, \frac{p_{c,1}}{p_{g,1}}, \frac{k}{k-1}, \frac{p_{g,1} l}{\mu_{g,1} c_{pg,1} T_{g,1}}, \frac{\lambda_{c,1}}{\lambda_{g,1}}, \frac{k}{k-1}, \frac{p_{c,1} l}{\mu_{c,1} c_{pc,1} T_{c,1}}, \frac{\lambda_m T_{g,1}}{p_{g,1} u_{g,1} l}, \frac{s}{l} \right) \quad (12)$$

显然,(11)、(12)式所含准则内容一样,但解的数学结构将不会一样。在提高实验的绝对压力水平、降低其绝对温度水平、即提高实验密流水平的条件下, $T_{w,g}$ 提高 η_1 降低,与此同时则 $T_{w,c}$ 降低而 η_2 增高,不仅提高叶片的平均温度且会使叶片热冷两边(沿叶片厚度方向)将有更大的温差 ΔT_w 及温梯,产生更大的热应力,而在冷端某些局部地区发生裂纹的可能性增大。

冷效实验器所用压力水平过低,无法模拟高压增压比发动机高压涡轮叶片的冷问题。如在低压水平下又错误地使用不相对应的更高的温度,则只能更加远离模拟点(新发动机的设计点)。

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EXPERIMENTAL STUDY ON PROPELLER FENCE FOR EFFICIENCY ENHANCEMENT AND NOISE REDUCTION

Mao Xichang, Li Hongmin, Wang Jiebing

(*Beijing University of Aeronautics and Astronautics*)

ABSTRACT

Three-blades scale-model propellers with and without propeller fence along the chord direction at 88% tip blade radius are compared experimentally in the wind tunnel in respect of aerodynamic and acoustic characteristics. Their rotational speeds vary between 1500rpm to 3000rpm. Experimental results indicate that under conditions of identical advance ratio J the efficiency of the propeller with propeller fence is enhanced 1.9% ~ 4.9% and its lower noise level is reduced 13~20dB. It is shown that the propeller fence is one of effective measures to increase efficiency and to decrease noise of propellers.

ON MODELLING CONDITIONS FOR COOLING EFFECTIVENESS EXPERIMENTS

Qiu Xuguang

(*Beijing University of Aeronautics and Astronautics*)

ABSTRACT

According to strict theory of similarity, the modelling conditions for model experiments on cooling blades or vanes of a gas turbine are obtained from a necessary set of differential equations and single-valued conditions. It is shown that when the pressure in modelling is lower than that in the actual turbine, the temperature in modelling must be lowered simultaneously in order to maintain the criterion on $pl/\mu \quad cpT$ for cooling air and for gas invariant. Therefore, it is necessary to increase the pressure and to decrease appropriately the temperature in modelling tests for the blades and vanes of high-pressure turbines with high pressure ratio.

SURFACE TEMPERATURE MEASUREMENT OF TURBINE DISKS

Wu Hongdao, Qu Yuwu, Li Xunguang, Du Shengqin

(*Design Institute of Xi'an Aero-Engine Corporation*)

ABSTRACT

A new method of temperature measurement with a single-wire thermocouple-slip ring system is first introduced to measure the surface temperature of the turbine disks in the turbojet engines and the accuracy of this method is considered in this paper. In this case the limited channels of the lip ring are fully utilized and the measured surface temperatures of the disk are actual and believable enough. The problems in its application such as the installation of the thermocouples, the cooling of the slip ring and the balance of the turbine rotor with this system are also discussed briefly.

NUMERICAL STUDY OF TURBULENT COMBUSTION MODEL

Zhao Jianxing and Yi Yong

(*Nanjing Aeronautical Institute*)

ABSTRACT

Although the $k-\epsilon$ turbulent combustion model becomes widespread in engineering application, but the coefficients of the model C_R , C_{g1} , C_{g2} and expressions of the square of concentration fluctuations g used by researchers are different. In