

近距离散冲击射流换热实验研究

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涡轮叶片内的冲击换热多取近距离散冲击换热 (冲击距与喷孔直径之比 $Z_n/d_n < 3$, 喷孔中心距与喷孔直径之比 $C_n/d_n < 3$)。由于在叶片前缘有气膜出流孔, 因而对叶片内前缘冲击换热做大面积平均实用意义较小。所以本实验旨在总结近距冲击下驻点连线及驻点附近小面积的换热规律并得出新的经验公式, 这具有较大的实用意义。

关键词: 冲击换热 换热系数 圆射流驻点

1 实验模型及实验系统

实验模型如图 1 所示。靶腔前缘为半径 30mm 的半圆柱凹腔, 总长 H 为 101mm, 靶腔宽度 B 为 50mm, 两侧壁为氟塑料板, 靶面用厚度为 0.5mm 的不锈钢板制成。采用电流直接通过靶面加热, 实验中靶面上各处热流密度相等 (靶面外侧包有绝热材料, 可忽略热损失)。靶面外侧面上在弦向及展向安排 39 对镍铬—考铜热电偶以测壁温。热电偶布置如图 1 所示。图 1 中喷管导管头部有安装各种形式喷管头的圆孔, 喷管头上可设计出不同形式的喷孔, 如图 2 所示, 以形成实验中不同尺寸的圆射流, 实验采用 4 种喷管头, 其喷孔尺寸及间距见表 1。

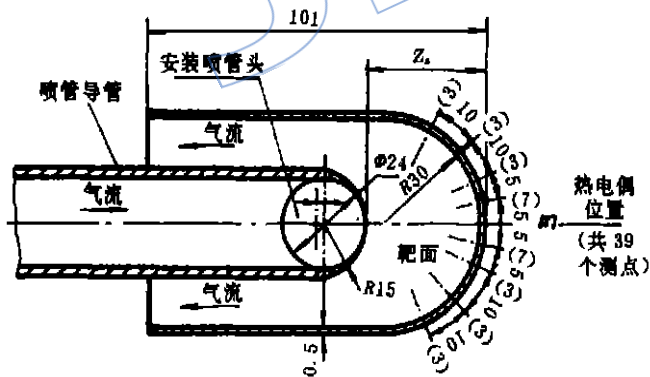


图 1 试验件组合简图

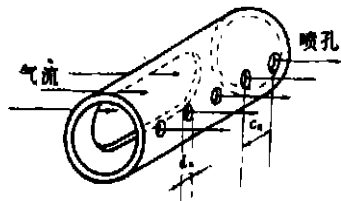


图 2 喷管头简图

由表 1 可看出 No. 2 至 No. 4 喷口射流总面积 f , 即当量缝宽 $b = f/B$ 基本相同。
实验设备气路系统: 供气压力为 6 个大气压, 气流经空气过滤器及调压阀进入稳压箱, 再

经孔板流量计进入喷管导管，经喷管头上的喷孔冲击到加热靶面上，然后由喷管导管两侧与靶面间的通道流入大气环境中。加热系统是以低电压大电流直接加热靶面。电流通过电流互感器用 0.2 级电流表测量，电压用电压表直接测量。加热量的改变通过调节自耦变压器实现。

表 1 实验用喷管头喷孔尺寸

管 号	孔数 n	孔径 d_n (mm)	孔中心距 C_n (mm)	$\frac{C_n}{d_n}$	当量缝宽 b (mm)	喷口面积 f (mm ²)
No. 2	5	5.10	9.43	1.85	2.04	102.14
No. 3	7	4.30	6.91	1.61	2.03	101.65
No. 4	9	3.80	5.56	1.46	2.04	102.07
No. 5	7	3.00	7.08	2.36	0.99	49.48

2 实验工况及数据处理

2. 1 实验工况

对 4 种不同的喷管头圆射流冲击加热靶面进行了 60 个工况的换热系数测定。在 $Z_n/d_n=3、2、1$ 每一 Z_n/d_n 下，以 5 种不同进气量进行换热实验 (Z_n 为喷孔至靶面距离，称冲击距； Z_n/d_n 称相对冲击距)。

2. 2 数据处理

(1) 热流密度 q 的计算 (忽略对外界的热损失)。 $q=IV/F$ (w/m^2)，式中 I 为加热电流 (A)； V 为加热电压 (V)； F 为靶面面积 (m^2)， $F=L \cdot B$ ， L 为加热面总长度 (m)。

(2) 雷诺数 Re 的计算。雷诺数中特征尺寸为两倍当量缝宽，则 $Re=G \cdot 2b/f \cdot \mu_f=G \cdot 2b/B \cdot b \cdot \mu_f=2G/B \cdot \mu_f$ 。式中 G 为气流流量， μ_f 为进气温度下空气的动力粘性系数。所以本实验中 Re 数实际表征冷气用量。

(3) 换热系数及努赛数计算。局部换热系数 α_i 定义为 $\alpha_i=q/(t_{ij}-t_f)$ ，式中 t_{ij} 为靶面上弦向位置 i ，展向位置 j 处的温度； t_f 为气流进气温度。弦向某处平均换热系数 α 为弦向 i 处沿展向局部换热系数 α_j 的算术平均值，即 $\alpha=\left[\sum_{j=1}^k \alpha_j\right] \setminus k$ ， k 为展向测点数目。在靶面弦向范围 A 面积内平均换热系数定义为： $\bar{\alpha}=\frac{1}{A} \int \alpha dA$ (采用近似计算梯形法求得)。

努赛数 $Nu=\bar{\alpha} \cdot 2b/\lambda$ ， λ 为空气在 t_f 下导热系数。本文中平均换热系数 $\bar{\alpha}$ 为在驻点小区中的平均换热系数。在 Nu 数下标 “1” 表示距驻点连线两侧 5mm 范围内的平均值；“2” 表示距驻点连线两侧 10mm 范围内的平均值。下标 “0” 表示驻点连线处的平均值。

3 实验结果及分析

(1) 给出在不同的 Z_n/d_n 下平均换热系数 α 沿弦向的分布曲线。如图 3、4 为 No. 3 及 No. 5 喷管的 α 分布，No. 2 与 No. 4 的 α 分布与 No. 3 的 α 分布图相似。由图中看出 α 沿弦向分布在近距范围内 ($Z_n/d_n=1 \sim 3$) 呈高斯曲线形式。且在相同的 Re 下随 Z_n/d_n 的减小是加大的。

(2) 在 $Z_n/d_n=1、2、3$ 范围内在各工况下求平均换热系数 $\bar{\alpha}_0、\bar{\alpha}_1、\bar{\alpha}_2$ 并整理出努赛数 $Nu_0、Nu_1、Nu_2$ 随雷诺数 Re 及相对冲击距 Z_n/d_n 变化的实验关联式，见表 2。

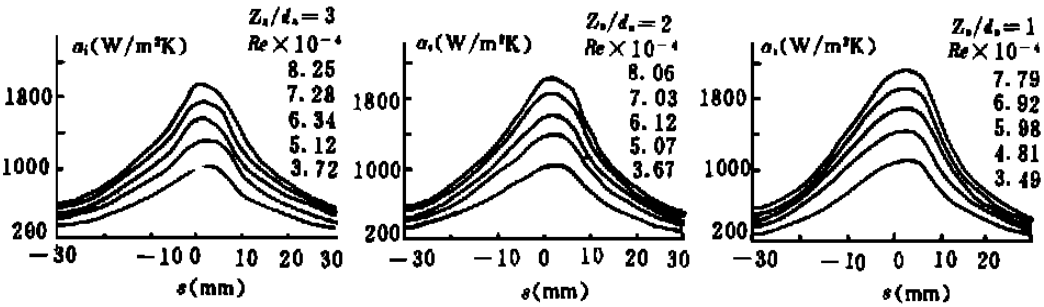


图 3 圆射流冲击流动换热系数 (No. 3) 分布

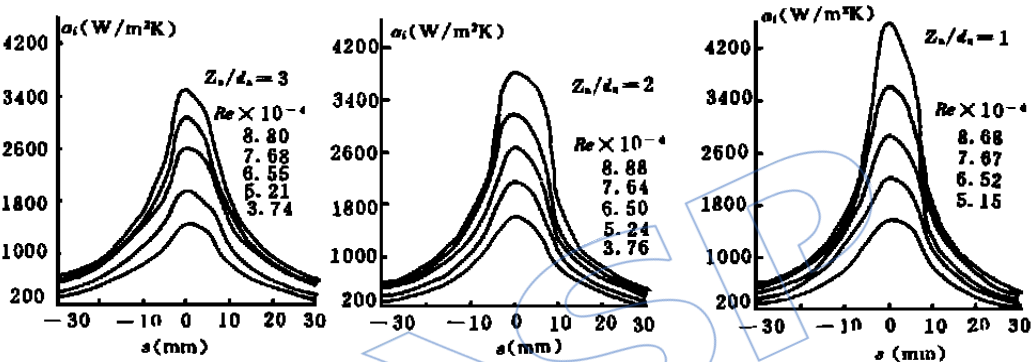


图 4 圆射流冲击流动换热系数 (No. 5) 分布

表 2 实验关联式

管 号	实 验 关 联 式	公式序号
No. 2 ($Z_n/d_n: 1\sim3$)	$Nu_0=0.04799Re^{0.7948}(Z_n/b)^{-0.1331}$	1
	$Nu_1=0.06565Re^{0.7636}(Z_n/b)^{-0.1340}$	2
	$Nu_2=0.07288Re^{0.7482}(Z_n/b)^{-0.1468}$	3
No. 3 ($Z_n/d_n: 1\sim3$)	$Nu_0=0.03204Re^{0.8290}(Z_n/b)^{-0.1230}$	4
	$Nu_1=0.03406Re^{0.8225}(Z_n/b)^{-0.1526}$	5
	$Nu_2=0.03435Re^{0.8150}(Z_n/b)^{-0.1618}$	6
No. 4 ($Z_n/d_n: 1\sim3$)	$Nu_0=0.02948Re^{0.8214}(Z_n/b)^{-0.04818}$	7
	$Nu_1=0.03201Re^{0.8118}(Z_n/b)^{-0.07492}$	8
	$Nu_2=0.03398Re^{0.8001}(Z_n/b)^{-0.08935}$	9
No. 5 ($Z_n/d_n: 1\sim3$)	$Nu_0=1.719\times10^{-3}Re^{1.0401}(Z_n/b)^{-0.1554}$	10
	$Nu_1=2.557\times10^{-3}Re^{1.0401}(Z_n/b)^{-0.1639}$	11
	$Nu_2=3.557\times10^{-3}Re^{0.9932}(Z_n/b)^{-0.1476}$	12
所有圆射流 实 验	$Nu_0=2.189\times10^{-2}Re^{0.8695}(Z_n/b)^{-0.1088}(C_n/d_n)^{-0.2433}$	13
	$Nu_1=3.035\times10^{-2}Re^{0.8410}(Z_n/b)^{-0.1231}(C_n/d_n)^{-0.3404}$	14
	$Nu_2=3.943\times10^{-2}Re^{0.8156}(Z_n/b)^{-0.1258}(C_n/d_n)^{-0.4752}$	15

图 5 为 No. 3 号喷管头的 Nu 与 Re 的关系曲线。其它号喷管头亦有类似的关系曲线。

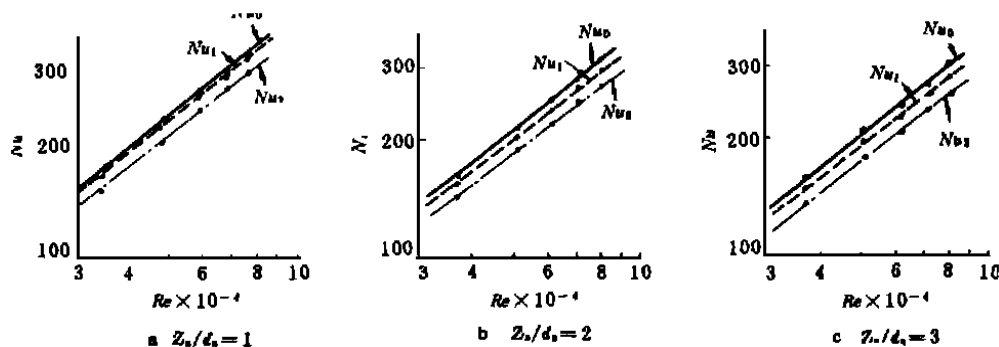


图 5 Nu 与 Re 的关系曲线 (No. 3)

(3) 对圆射流, 当开孔面积相同 (即当量缝宽 b 不变), 流量相同 (即雷诺数 Re 不变), 对于相同的相对冲击距 Z_n/d_n 随开孔数目 n 增大, 亦即 C_n/d_n 变小 ($C_n/d_n \propto 1/\sqrt{n}$), 由表 2 中关联式 (13) ~ (15) 看出在此情况下散布的小孔换热比集中大孔换热要好, 且随平均换热区域加大效果愈显著。这由于当 n 增大 d_n 变小 (开孔面积不变) 各孔流束收缩更甚, 使实际出流面积变小, 形成更高流速 (更高的密度) 的射流, 因而有更强的换热。

(4) 实验中 No. 3 与 No. 5 喷管头、孔数目相同而孔径不同, 它们的实验关联式中, Re 的指数在 d_n 小时 (No. 5) 比 d_n 大时 (No. 3) 要增大 21~31%, 这主要是因为 Re 相同时实质是具有相同的流量。由于 No. 5 开孔面积小而使流速加大, 显而易见会使换热强度大大加强。

(5) 由于本实验弦向平均换热系数 α 值, 采用展向局部换热系数 α_y 的平均值, 使 α 数值更可靠。又拟合的经验公式采用驻点小区的平均换热系数, 所以拟合的实验关联式更具实用意义。实验发现驻点线两侧弦向位置对称点处, 实验值 (α_y) 不完全相等, 总在一侧偏大。由于靶腔与喷管导管中线不对正, 有微小系统偏差所致, 但不影响实验结果的规律性。

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TECHNICAL NOTES

INFLUENCE OF RADIATION HEAT LOSS OF ENCLOSURE ON WALL TEMPERATURE OF JET NOZZLE

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ABSTRACT

Using the apparent emissivity, the net heat loss of the radiation from the enclosure surface due to passing through the open end of the enclosure was calculated. The influence of the net heat loss on surface temperature was also discussed. Results showed that the net heat loss on the downstream side of the jet nozzle could reach 20 ~ 30% of total heat flux. Therefore it can not be neglected in calculating the wall temperature.

NUMERICAL ANALYSIS OF AERODYNAMIC LOSSES IN FILM-COOLED VANE CASCADE

Jiang Tao, Fan Weihong, Liu Songling

(Northwestern Polytechnical University)

ABSTRACT

"Integral Boundary-Layer Parameter" method based on a 2-dimensional film-cooling flow and heat transfer prediction program STANCOOL is provided to predict the aerodynamic losses in the film-cooled vane cascade. The comparison of the numerical analysis with the corresponding experimental data demonstrates that the present method is more suitable to the case when blowing rates are low or the film cooling is located at thick local boundary layer. Finally this method is compared with another loss predicting method, named "TOTLOS", and it is concluded that both methods have their own advantages and extent of application. In practice it is reasonable to use the two methods in combination.

EXPERIMENTAL STUDY ON HEAT TRANSFER OF SEPARATED IMPINGEMENT JETS IN SHORT DISTANCE

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(Beijing University of Aeronautics and Astronautics)

ABSTRACT

In actual cooling construction of turbine blade the relative distance between circular jets c_n/d_n is less than 3 and the relative distance of nozzle exit to target surface is also less than 3. But the available empirical formulas were achieved on the basis of very large range of these geometric parameters. Obviously, these formulas may be inaccurate in the practical narrow range of these parameters, in particular when the temperature of the turbine is very high, and on the surface of the blade exist many rows of film-cooling holes. So an experimental research on the heat transfer of impingement jets has been carried out in the actual range of the geometric parameters and new empirical formulas have been

established, which can be applied to the turbine blade of the advanced aeroengine.

A NEW WAY TO SOLVE STEADY CREEP PROBLEM WITH FINITE ELEMENT METHOD

Mu Xiaying and Wang Jiwei

(Xi'an Jiaotong University)

ABSTRACT In this paper, a new way to solve steady creep with finite element method is presented for temperature-dependent material properties of symmetric body. According to different material properties, initial strain rate method and general tangential stiffness method are provided. A computing program is compiled. Some examples are analysed numerically to check its convergency and applicability.

ON ENGINE PARAMETER ESTIMATION WITH FLIGHT TEST DATA

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(Northwestern Polytechnical University)

Li Shuren and Xin Xiaowen

(Flight Test Research Institute)

ABSTRACT This paper introduces the parameter estimation research for the turbine inlet temperature and compressor exit pressure by using the engine variables measured under the different flight conditions. The parameter estimation method is multiple linear regression analysis. The independent variables in the regression equations have been selected from six measured engine variables based on the comprehensive optimal principle about variable selection. The regression models which have been established only include three measured engine variables. The curves of the parameter estimation results shown in this paper demonstrate that the estimation accuracies of these models are satisfactory. This paper also presents the data treatment methods of engine variables recorded on-line with special equipment.

AN AERODYNAMIC DESIGN PROGRAM FOR CONTRA-ROTATING TURBINE CASCADES

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(Institute of Engineering Thermophysics)

Wei Xinglu

(Beijing University of Aeronautics and Astronautics)

ABSTRACT An extremely simple, rapid and universal turbine cascade design program is developed for contra-rotating turbine cascades. With its simplest operating condition, only four data are necessary to be input for obtaining the geometry of a good enough cascade. They are just the input data for designing a cascade- the inlet Mach number and flow angle, the outlet Mach number and the specific heat ratio of working substance. Therefore, it means that the design can be accomplished without any additional human