航空燃气涡轮发动机压气机气体动力学计算算法

算法理论基于参考书

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Ⅰ 单轴轴流式压气机气体动力学简化计算

§Ⅰ.Ⅰ 压气机第一级基础数据的选择

原始数据 ① 飞行高度 $H=0$

② 飞行速度 $V_H=0$ $M_H=\frac{V_H}{a_H}=0$ 注：M 为马赫数 = Ma，a 为声速

③ 标准地面条件 $T^*_H=288\ K$. $P^*_H=1{,}014\cdot10^5$ Па.

④ 空气流量 $G_{B\,\#}=?$

⑤ 压比 $\pi_K^*=?$

⑥ 压气机绝热效率 $\eta_K^*=?$ （通常 $\eta_K^*=0{,}84\div0{,}86$）目标、

⑦ 进气装置总压恢复系数 $\delta_{Bx}=?$

原始数据之选择取决于工况及压气机设计

其余数据：

① 相关系数 / степень реактивности

$$\rho_K=\frac{\frac{W_1^2-W_2^2}{2}\ \ M^2/c^2}{H_T\ \ КДж/кг,\ M^2/c^2}$$

$\rho_K=0{,}55\div0{,}6$，理想情况下 $\rho_K=0{,}5$

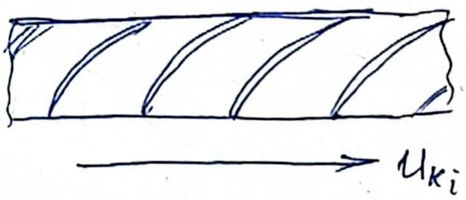
②. 相对直径.

$$\overline{d_{BT}}=\frac{d_{BT}}{D}$$，d_{BT} — Диаметр втулки, 叶根部直径

轮缘 $\overline{d_{BT}}$ 取 $0{,}35\div0{,}6$.

③ 切向速度，~~平均切向速度~~.

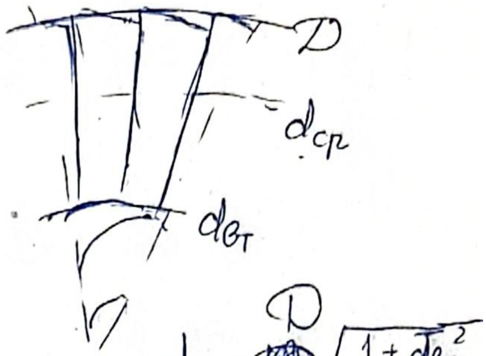
$U_{K_1}=330\div360$ м/с.



④ 叶心切向速度

$$u_{cp1} = u_{k1}\cdot\sqrt{\frac{1+\bar{d}_{BT}^2}{2}}$$

相对 叶心



$$d_{cp} = D\sqrt{\frac{1+\bar{d}_{BT}^2}{2}}$$

⑤ 理论水头 (напор)

$$\bar{H}_{th1} = 0,25 \div 0,4$$

$$H_{th} = \bar{H}_{th}\cdot u_{cp}^2 \quad , \quad кДж/кг$$

⑥ 轴向速度 C_{1a}，流量系数？$\bar{C}_{1a} = \frac{C_{1a}}{u_{cp1}}$，

第一级气流于叶心的来流角度 α_1

$$ctg\,\alpha_1 = \frac{2(1-\rho_k) - \bar{H}_{th1}}{2\bar{C}_{1a}} \quad \boxed{*1}$$

$\bar{H}_{th1}$ ρ_k $\bar{d}_{BT1}$ 和 u_k.

可由 $q(\lambda)$ 保证，其中

$$q(\lambda) = \frac{\rho c}{\rho^* c^*} = \left(\frac{k+1}{2}\right)^{\frac{1}{k-1}}\cdot\lambda\cdot\left(1-\frac{k-1}{k+1}\lambda^2\right)^{\frac{1}{k-1}}$$

*1 推导

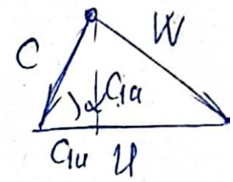
$$2(1-\rho_k) = \frac{C_1^2 - C_2^2}{u(C_{2u}-C_{1u})} = \frac{C_{1u}+C_{2u}}{u}$$

$$-\bar{H}_{th1} = -\frac{H_{th1}}{u_{cp}^2} = +\frac{C_{1u}-C_{2u}}{u_{cp}}$$

$$2\bar{C}_{1a} = \frac{2C_{1a}}{u_{cp}}$$

$$\frac{2(1-\rho_k)-\bar{H}_{th1}}{2\bar{C}_{1a}} = \frac{\frac{C_{1u}+C_{2u}}{u}+\frac{C_{1u}-C_{2u}}{u}}{\frac{2C_{1a}}{u_{cp}}}$$

$$= \frac{C_{1u}}{C_{1a}}.$$



$$Ctg\alpha = \frac{C_{1u}}{C_{1a}}$$

⑦ 流量系数

$$\bar{G}_k = (1-\bar{d}_{BT}^2)\,q(\lambda_1)\,Sin\,\alpha_1$$

где:

$$\lambda_1 = \frac{\lambda_{1a}}{Sin\alpha_1} = \frac{C_{1a}}{a_{1a}\,Sin\alpha_1}.$$

$$a_{kp} = \sqrt{\frac{2kRT^*}{k+1}} = 18,3\sqrt{T^*}$$

对于第一级 接近极限值

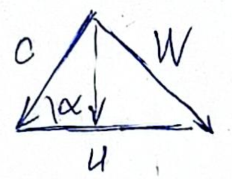
$$\bar{G}_k = 0,65$$

⑧ λ 口马赫数

$$M_{W1} = \cancel{\frac{\alpha_{1kp}}{\alpha_1}}\ \frac{a_{1kp}}{a_1}\sqrt{\lambda_1^2+\lambda_u^2-2\lambda_1\lambda_u\cos\alpha_1} = \lambda_w = \frac{W}{a_{1kp}}.$$

外缘速度系数 相关

对于



$$\lambda_u = \frac{u_{cp1}}{a_{1kp}}$$

$$\frac{a_{1kp}}{a_1} = \frac{1}{\sqrt{\frac{k+1}{2}\tau(\lambda_1)}} \qquad \frac{T}{T^*} = \tau(\lambda) = 1 - \frac{k-1}{k+1}\lambda^2$$

$$M_{W1} = 0,75 \div 0,8.$$

⑨ 切向速度马赫数 *

$$M_u = \frac{M_{u1}}{\sqrt{\bar{C}_{1a}^2+(\rho_k+\frac{\bar{H}_{th1}}{2})^2}}$$

在入口处的声速：

$$a_1 = \frac{a_{1kp}}{\frac{a_{1kp}}{a_1}} \quad *$$

轮缘速度：

$$u_{cp1} = a_1 \cdot M_u$$

⑩ 叶片密度：

采用如下无量纲数计算：

$$\frac{\bar{H}_{th1}}{\bar{C}_{1a}}, \quad \frac{\rho_K}{\bar{C}_{1a}}$$

有经验公式：

$$\left(\frac{\bar{H}_{th}}{\bar{C}_{1a}}\right)_{b/t=1.0} = 0.7 - 0.27\frac{\rho_k}{C_a} + 0.16\left(\frac{\rho_k}{C_a}\right)^2$$

计算 $\left(\frac{\bar{H}_{th}}{\bar{C}_{1a}}\right)_{b/t=1.0}$ 和实际 $\frac{\bar{H}_{th}}{\bar{C}_{1a}}$

以计算 b/t，有

$$J = \frac{\bar{H}_{th1}/\bar{C}_{1a}}{(\bar{H}_{th1}/\bar{C}_{1a})_{b/t=1.0}}$$

$$\frac{b}{t} = 0.225 + 0.275J + 0.5J^2$$

⑪ 在第一级涡轮做的功

$$H_{k1} = \frac{H_{th1}\cdot\Omega}{\eta_3\cdot\eta_f}$$

η_3 为缝隙损失.

η_f 为摩擦损失

$\eta_3\cdot\eta_f$ ~~aaa~~ 对于第一级 $0.97\div0.98$

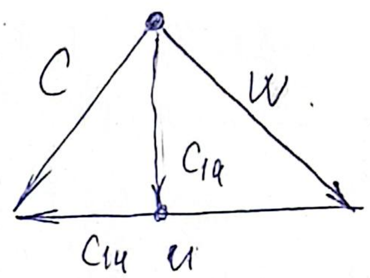
$\Omega = 0.98\div1.0$

$$M_u = \frac{M_{w1}}{\sqrt{\bar{C}_{1a}^2+(\rho_k+\frac{\bar{H}_{th1}}{2})^2}}$$

$$= \frac{M_{w1}}{\sqrt{\frac{C_{1a}^2}{u^2}+\left(1-\frac{C_{1u}+C_{2u}}{2u}+\frac{C_{2u}-C_{1u}}{2u}\right)^2}}$$

$$= \frac{M_{w1}}{\sqrt{\frac{C_{1a}^2}{u^2}+\frac{(u-c_{1u})^2}{u^2}}}$$

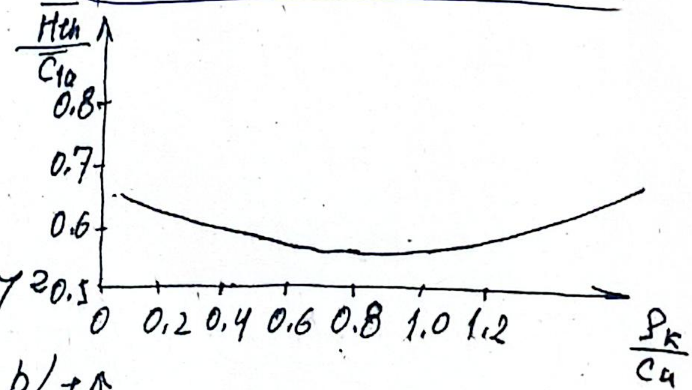
速度三角形：

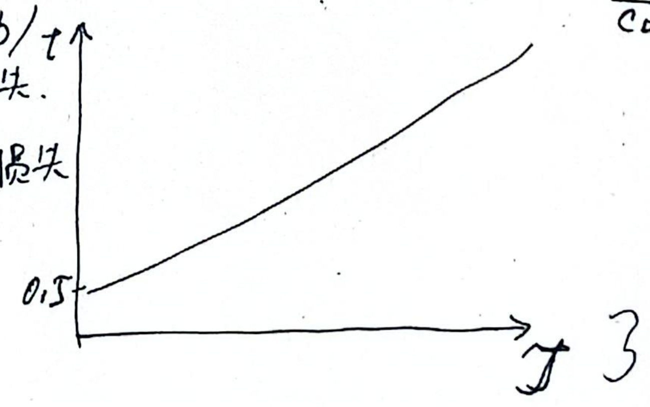


$$c_{1a}^2+(u-c_{1u})^2 = W^2.$$

поэтому:

$$M_u = \frac{M_{w1}}{W/u}$$





⑫. 第一级直径.

$$D_{K1} = \sqrt{\frac{4G_B \cdot \sqrt{T_B^*}}{\pi \cdot S_B \cdot p_B^* \cdot \bar{G}_K \cdot K_G}}$$

$$p_B^* = P_H^* \cdot \delta_{Bx}$$

$$S_B = \sqrt{K\left(\frac{K}{K+1}\right)^{\frac{K+1}{K-1}} \cdot \frac{1}{R}} = 0{,}0404.$$

$K = 1{,}4$, $R = 287{,}3$ Дж/кг

K_G表征了沿叶片方向速度场的不均匀性, 通常取:

при $g_K = Const$ $K_G = 0{,}93 \div 0{,}95$,

при 环流定律 $K_G = 0{,}97 \div 0{,}98$

при 二者间 $K_G = 0{,}95 \div 0{,}97$.

при $M_H \le 1{,}0$, $\delta_{Bx} = 0{,}96 \div 0{,}98$

$M \le 1{,}5$ $\delta_{Bx} = 0{,}92 \div 0{,}96$

§ I.2 压气机预先计算

在该算例中采用 $D_{cp} = Const$.

①. $D_{cp} = Const$ 情况下的平均功 (水头).

$$H_{Kcp} = (1{,}3 \div 1{,}5) \cdot H_{K1}.$$

② 压气机总功 (水头)

$$H_K = \frac{K}{K-1} R T_H^* \left(\pi_K^{*\frac{K-1}{K}} - 1\right) \frac{1}{\eta_K^*}.$$

③ 压气机级数.

$$Z = \frac{H_K}{H_{Kcp}}$$ 并 取整.

④ 功率

$$N_K = G_B \cdot H_K$$

⑤ 压气机转子转速

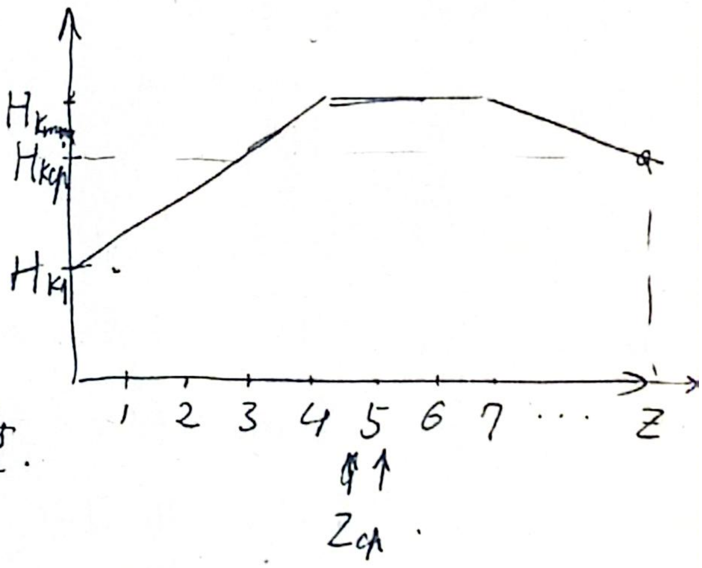
$$n = \frac{U_{K1}}{\pi \cdot D_{K1}}$$ об/с.

⑥. 通常认为中间级之后2－3级达到最大值，约 1.1÷1.2倍 H_{Kcp}.

对于偶数级 $z_{cp}=\frac{z}{2}$，对于奇数级 $z_{cp}=\frac{z+1}{2}$.

需使末级 H_{Kz} 达到 H_{Kcp}，

且总和等于 H_K.



⑦ 轴向速度 C_{ia} 随着级数增加而逐渐减小

通常认为两级间轴向速度梯度

不大于 10÷15 м/c.

且 $\overline{Ca_K}\geq 0.45\div 0.5$；$\lambda_K=0.35\div 0.45$ ⑧ $C_K=140\div 170$ м/c.

$$\overline{Ca_K}=\frac{C_K}{\cancel{C_{cp}}\cdot U_{cp}}\qquad \lambda_K=\frac{C_K}{a_{Kp}}\qquad T_K^*=T_H^*+\frac{H_K}{\frac{K}{K-1}R}$$

查表/通过公式可得 $q(\lambda_K)$

压力.

$$P_K^*=\delta_{Bx}\cdot P_H^*\cdot\pi_K$$

压气机出口截面面积.

$$F_K=\frac{G_B\cdot\sqrt{T_K^*}}{P_K^*\cdot q(\lambda)\sin\alpha_K\cdot S_B\cdot K_G}$$

~~中间截面~~ 平均直径.

$$D_{cp}=D_{K1}\cdot\sqrt{\frac{1+\overline{d_{BT}}^2}{2}}$$

出口导向叶片高度

$$h_{C.A.K}=\frac{F_K}{\pi\cdot D_{cp}}$$

由此可推出：

$$\overline{d_{BT,K}}=\frac{2\left(\frac{D_{cp}}{h}\right)^2+\sqrt{4\left(\frac{D_{cp}}{h}\right)^2-1}}{2\left(\frac{D_{cp}}{h}\right)^2-1}$$

$$D_{K1}=\frac{D_{cp}}{\sqrt{\frac{1+\overline{d_{BT}}^2}{2}}},\qquad d_{BT}=\frac{D_{cp}\cdot\overline{d_{BT,K}}}{\sqrt{\frac{1+\overline{d_{BT}}^2}{2}}}$$

⑨ 相关系数通常随着级数的增长每级增加 1÷3%

$$\rho_{K i+1} = \rho_{Ki} \cdot (1.01 \div 1.03).$$

⑩. 理论单级水头功

$$\underset{\text{轴向}}{H_{th_i}} = H_{Ki} \frac{(\eta_3 \cdot \eta_f)_i}{\Omega_i}$$

Ω_i 表征速度场不均匀性.

第一级取 0.98÷1.0.

最后一级取. 0.86÷0.9.

$\eta_3 \cdot \eta_f$ 表示压气机效率, 第一级取 0.97÷0.98,

最后一级取 0.95÷0.96.

⑪. 水头系数及流量系数.

$$\overline{H_{th_i}} = \frac{H_{th\,i}}{u_{cp}^2}; \quad \overline{C_{ai}} = \frac{C_{ai}}{u_{cp}}.$$

⑫. $(b/t)_{h.t.}$ 和 $(b/t)_{c.A}$ ~~不应~~ 对于亚音速压气机不应高于 1.5÷1.6, 由前式得出.

转子后的轴向速度.

$$C_{2a\,i} = \frac{C_{1ai} + C_{1a\,i+1}}{2}$$

转子后的切向速度.

$$C_{2u\,i} = u_{cp}\left[(1-\rho_K) + \frac{\overline{H_{th}}}{2}\right] *$$

$$* \; (1-\rho_K) + \frac{\overline{H_{th}}}{2} = \frac{\frac{C_{2u}^2 - C_{1u}^2}{2}}{H_{th}} + \frac{C_{2u} - C_{1u}}{2u_{cp}} = \frac{2C_{2u}}{2u_{cp}} = \frac{C_{2u}}{u_{cp}}.$$

气流方向.

$$\alpha_{2_i} = \operatorname{arctg} \frac{C_{2ai}}{C_{2ui}}.$$

$$\alpha_{3i-1} = \alpha_{1i} = \operatorname{arctg} \frac{C_{1a\,i}}{C_{1u\,i}}$$

其中 $C_{1u} = u_{cp}\left[(1-\rho_K) - \frac{\overline{H_{th}}}{2}\right]$

导向叶片气流转折角.

$$\Delta\alpha = \alpha_{3i} - \alpha_{2i}$$

由经验公式

$$(\Delta\bar{\alpha})_{b/t=1} = 0,37 + 0,1\bar{\alpha}_3 + 0,262\bar{\alpha}_3$$

$$\Delta\bar{\alpha} = \frac{\Delta\alpha}{100}, \quad \bar{\alpha}_3 = \frac{\alpha_3}{100}.$$

$$E = \frac{\Delta\bar{\alpha}}{(\Delta\bar{\alpha})_{b/t=1}}$$

$$\left(\frac{b}{t}\right)_{C.A} = 10(0,981 - 1,788E + 0,912E^2)$$

若 $\frac{b}{t}$ 超过极限，应当重新分配每级的压力头.

⑬. 每级的效率.

在初始级. $\eta^*_{K.CT} = 0,84 \div 0,86.$

中间级. $\eta^*_{K.CT} = 0,89 \div 0,9.$

末级 $\eta^*_{K.CT} = 0,86 \div 0,87.$

$$\frac{\eta_v}{\eta^*_{\ni}} = 1 - \frac{H_{Kz}}{H_K}(1 - \eta^*_{Kz}.)$$

$$\eta^*_{\ni v} = \frac{\frac{K-1}{K}\lg\pi_K^*}{\lg\left(1 + \boxed{\frac{\eta_v}{\eta^*_{\ni v}}}\frac{\pi_K^{\frac{K-1}{K}} - 1}{\eta^*_K}\right)}$$

$$\eta^*_v = \frac{\eta_v}{\eta^*_{\ni v}} \cdot \eta^*_{\ni v}.$$

Далее находим:

$$\sum_1^z H_{Ki} \cdot \eta^*_i = H_K \cdot \eta_v$$

⑭ 滞止温度.

$$T^*_{1(i+1)} = T^*_{3i} = T^*_{2i} = T^*_{1i} + \frac{H_{Ki}}{\frac{K}{K-1}R}.$$

(15). 压比.

$$\pi_{ki}^* = \left(\frac{H_{ki} \cdot \eta_{ki}^*}{\frac{k}{k-1} R T_{1i}^*} + 1 \right)^{\frac{k}{k-1}}$$

$$\prod \pi_{ki}^* = \pi_k^*.$$ для проверки.

$$P_{1\,i+1}^* = P_{3i}^* = P_{1i}^* \cdot \pi_{ki}$$

对于第一级

$$\pi_{kI}^* = \frac{P_{3I}^*}{P_B^*}.$$

1.3. 中间截面参数计算.

1. 转子入口处切向速度.

$$C_{1ui} = U_{cp1\,i}\left[(1-\rho_{ki}) - \frac{\overline{H_{thi}}}{2}\right]$$

2. 绝对速度.

$$C_{1i} = \sqrt{C_{1ui}^2 + C_{1ai}^2} \qquad \lambda_{1i} = \frac{C_{1i}}{a_{1kpi}} \qquad a_{1kpi} = \sqrt{\frac{2k}{k+1} R T_{1i}^*}$$

3. 气流进入角度.

$$\alpha_{1i} = \arcsin \frac{C_{1ai}}{C_{1i}} \qquad \alpha_{1i} = \alpha_{3(i-1)}.$$

4. 截面面积.

$$F_{1i} = \frac{G_B \sqrt{T_{1i}^*}}{P_{1i}^* \cdot q(\lambda_1)_i \cdot \sin\alpha_{1i} \cdot S_B \cdot K_G}.$$

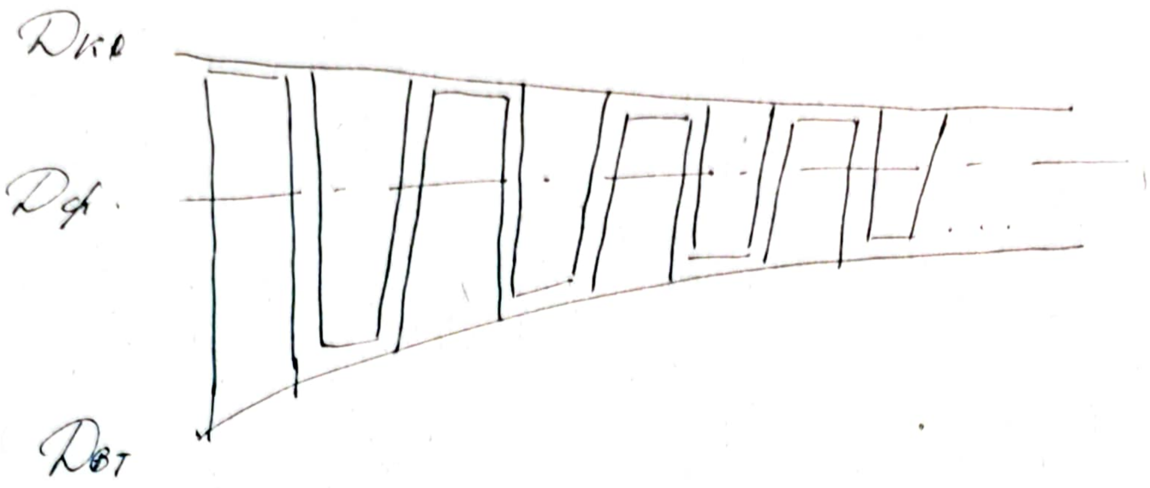
5. D_{k1i}, D_{BT1i} 由前式得出.

1.4. 压气机结构示意图及表格.

Таблица I

Ступени.

Параметры	I	II	III	IV	V	VI	VII	VIII	IX	X	…
H_{ki}											
C_{1ai}											
ρ_{ki}											
Ω_i											
$(\eta_3 \cdot \eta_4)_i$											
H_{thi}											
$\bar{H}_{thi}$											
$\bar{C}_{1ai}$											
η^{*}_{ki}											
$H_{ki} \cdot \eta_{ki}$											
T^{*}_{3i}											
T_{1i}											
π^{*}_{k}											
P^{*}_{1i}											
C_{1ui}											
C_{1i}											
a_{1kpi}											
λ_{1i}											
$q(\lambda_1)_i$											
α_{1i}											
$\sin \alpha_{1i}$											
F_{1i}											
$h_{1i} = h_{3(i-1)}$											
D_{k1i}											
D_{BT1i}											
$\bar{h}_i$											
δa_i (经验.											
β_i ~~[illegible]~~											
ξ_i											
ξ_{ai}											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