第 5 卷　第 2 期　　航空动力学报　　Vol. 5　No. 2
1990 年　4 月　　Journal of Aerospace Power　　Apr.　1990

计算流体对数平均温差和换热面积的解析式

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一、回热器内对数平均温差解析式的推导

准确地计算回热器中冷热两种流体对数平均温度差和换热表面积，是保证按回热循环工作的燃气轮机具有高的热效率和节约金属材料的重要条件。

右图给出了燃气和空气的温度沿回热器流动方向变化的情况。燃气进入回热器时的温度为 t_4，由于沿程放出热量温度不断下降，在出口处燃气温度下降到 t_5。压缩空气进入回热器的温度为 t_2，由于在回热器内回收燃气的余热，故温度不断上升，空气离开回热器出口的温度为 t_{2R}，燃气和空气的温度差是不断变化的，因此在利用传热方程式 $Q = kF\Delta t_m$ 来计算整个传热面上的热流量或换热面积时，必须使用整个传热面积上的平均温度差。当换热器内两种流体作逆流运动时两种流体在回热器入口处的温度差 $\Delta t'' = t_5 - t_2$，在出口处的温度差 $\Delta t' = t_4 - t_{2R}$。由理论推导得对数平均温差的公式为：

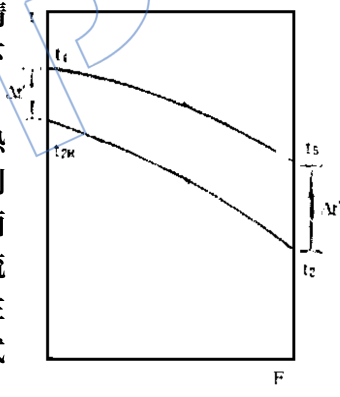

图 1　回热器内燃气和空气温度变化

$$\Delta t_m = (\Delta t'' - \Delta t')/\ln(\Delta t''/\Delta t')$$
$$= [(t_5 - t_2) - (t_4 - t_{2R})]/\ln[(t_5 - t_2)/(t_4 - t_{2R})] \qquad (1)$$

在燃气轮机热力计算中只知道 t_2 和 t_4，因此要计算它们的对数平均温度差，必须求出 t_{2R} 和 t_5，为此要应用回热度 f 的定义式（2）求 t_{2R} 和能量守恒式（3）求 t_5。

$$f = \bar{c}_{pa}(t_{2R} - t_2)/(1 + g_T)\bar{c}_{pa}(t_4 - t_2) \qquad (2)$$

$$(1 + g_T)\bar{c}_{pa}(t_4 - t_5) = \bar{c}_{pa}(t_{2R} - t_2) \qquad (3)$$

式中 $\bar{c}_{pa}$ 和 c_g 是空气和燃气在回热器中的平均等压比热；g_T 是每公斤空气的燃油量（或称油气比）。将（1）式改写为下列形式：

$$\Delta t_m = \frac{[(t_{2R} - t_2) - (t_4 - t_5)]}{\ln\{(t_5 - t_2)/[(t_5 - t_2)/(t_4 - t_2) - (t_{2R} - t_2)]\}} \qquad (4)$$

利用式（2）和式（3），用（$t_{2R} - t_2$）表示（$t_4 - t_5$）、（$t_4 - t_2$）和（$t_5 - t_2$）代入（4）式

$$\Delta t_m = \frac{[1 - (1 + g_T)^{-1}(\bar{c}_{pa}/\bar{c}_{pg})](t_{2R} - t_2)}{\ln\{(1 + g_T)^{-1}(\bar{c}_{pa}/\bar{c}_{pg})(f^{-1} - 1)/[(1 + g_T)^{-1}(\bar{c}_{pa}/\bar{c}_{pg})f^{-1} - 1]\}} \qquad (5)$$

本文于 1989 年 4 月收到。

或者用涡轮出口燃气温度与压气压出口空气的温度差（t_4-t_2）表示得:

$$\Delta t_m=\frac{[(1+g_T)(\bar{c}_{pa}/\bar{c}_{pg})-1]f(t_4-t_2)}{\ln\{(1+g_T)^{-1}(\bar{c}_{pa}/\bar{c}_{pg})(f^{-1}-1)/[(1+g_T)^{-1}(\bar{c}_{pa}/\bar{c}_{pg})f^{-1}-1]\}} \tag{6}$$

显然，根据燃气轮机热力计算可知 t_2 和 t_4，利用式（6）计算不同 f 时的 Δt_m，由上式可见（t_4-t_2）越大，Δt_m 也越大，此外计算结果表明 f 越大，Δt_m 也越小（表 1）。

表 1 WJ-6G 和 WZ-6G 机组不同 f 时的 Δt_m

f		0.65	0.70	0.75	0.80
Δt_m	WJ-6G	52.2	44.3	36.4	28.6
	WZ-6G	107.5	91.2	74.9	58.6

二、回热器传热面积解析式的推导

在回热器中燃气和空气为交叉流动，因此应在逆流对数平均温差公式前乘以修正系数 ψ，它的值可根据一般《换热器设计手册》等资料中查得。根据燃气和空气在回热器中交换的热量，应等于空气所吸收的热量可得

$$\psi kF\Delta t_m=G_a\bar{c}_{pa}(t_{2R}-t_2) \tag{7}$$

将式（5）代入式（7）得计算燃气轮机空气流量为 G_a 时，回热器总的传热面积 F 的:

$$F=\frac{G_a\bar{c}_{pa}}{\psi k}\frac{\ln\{(1+g_T)^{-1}(\bar{c}_{pa}/\bar{c}_{pg})(f^{-1}-1)\}}{1-(1+g_T)^{-1}(\bar{c}_{pa}/\bar{c}_{pg})} \tag{8}$$

用 G_a 除上式两边，即可得每公斤空气流量时回热器的换热面积。

目前，有些文献［1］建议采用苏联学者乌伐洛夫公式来计算回热器的总传热面积。

$$F=(G_a\bar{c}_{pa}/k)[f/(1-f)] \tag{9}$$

为了检验其准确性，我们分别用下列两式计算了不同 f 的值，计算结果见表 2。

$$(f/1-f) \tag{A}$$

$$ln\{(1+g_T)^{-1}(\bar{c}_{pa}/\bar{c}_{pg})(f^{-1}-1)/[1-(1+g_T)^{-1}(\bar{c}_{pa}/\bar{c}_{pg})]\} \tag{B}$$

表 2 f 值不同时式（A）和式（B）的计算值及其相对误差［以（B）式的计算值为准］

回热度 f	0.65	0.70	0.75	0.80	0.85
（A）式计算值	1.8571	2.3333	3.0000	4.0000	5.6667
（B）式计算值	2.0065	2.5467	3.3226	4.5310	6.6802
相对误差（%）	7.45	8.83	9.71	11.72	15.17

表 2 表明，用（9）式计算的值偏低，而且随着 f 增大，误差也越大。原因是：该式没有考虑空气和燃气比热的差别；也没有考虑在回热器内空气流量与燃气流量不相等，实际上当涡轮进口处燃气的温度较高时，g_T 的影响是不能忽略的；最后，最重要的一个原因，乌伐洛夫用温差（t_4-t_{2R}）来近似的代表 Δt_m 造成误差。

参 考 文 献

［1］ 尾花英朗著，“换热器设计手册”，石油工业出版社，1984 年。

TECHNICAL NOTES

AN EXPERIMENTAL INVESTIGATION OF ROTATING STALL IN A CENTRIFUGAL COMPRESSOR WITH VANELESS DIFFUSER

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ABSTRACT This paper deals with experimental investigation of unsteady flow in a radial vaneless diffuser. The circumferentially uniform discharge at the exit of the diffuser changes into a periodic circumferentially fluctuating flow state. The experimental measurements show that the properties of rotating stall in the diffuser are very obvious. The results of the investigation indicate that two type of rotating velocity patterns occur successively as the flow rate decreases. Their rotational speeds are different and the pattern with low rotational speed firstly appears.

VALUATION OF FLOW-INDUCED FORCE IN LABYRINTH SEAL

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ABSTRACT The continuity equation and momentum equation of the flow through a sectorial element in labyrinth seal is linearized according to the presumption of the small disturbance and solved with the aid of matrix method. Then the distribution of the pressure on the cylindrical surface of rotor is obtained. Finally, the flow-induced force on rotor is evaluated by means of integration. Numerical example indicates that as the number of seal chamber increases, the flow-induced force increases while the leakage flow rate decreases; when the seal clearance increases, the flow-induced force decreases while the leakage flow rate increases; but both the flow induced force and leakage flow rate decrease when the exit pressure increases.

ANALYTICAL FORMULAS FOR LOGARITHMIC MEAN TEMPERATURE DIFFERENCE AND HEAT-EXCHANGE AREA

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ABSTRACT In order to save energy and metallic material, it is very important to calculate the logarithmic mean temperature difference between the two kinds of fluids and the superficial area of the heat exchanger accurately. The traditional calculational method is too complicated, but the error of simplified method is too significant, so we deduce the formulas for logarithmic mean temperature difference between the cold and hot fluids in a heat exchanger in consideration of their thermophysical properties and the formula for sueperficial area of the exchanger. The formulas are easy to use and give accurate results.