

假想8步建立流动 (Ramjet).

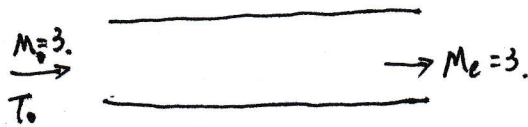
$M_0=3$... 来流马赫数为3.

T_0 来流静温

T_{t0} 来流总温

$Me=3$... 出口马赫数为3.

① step 1 等直管.

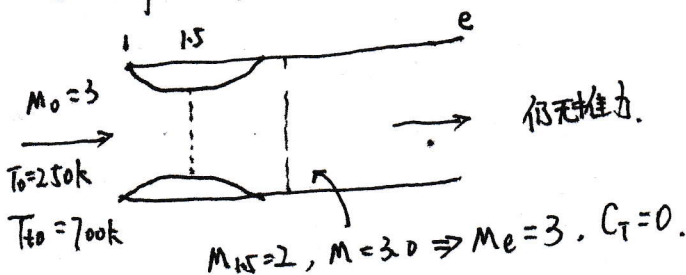


很明显, 进口、出口状态相同, $C_T=0$.

$$\text{推力系数 } C_T = \frac{F_T}{P_0 A_0} = \gamma M_0^2 \left(\frac{V_e}{V_0} - 1 \right) + \frac{A_e}{A_0} \left(\frac{P_e}{P_0} - 1 \right)$$

有无推力就看它了.

② step 2 加进气道



1—进气道口. 1.5—进气道喉部.

3—燃烧室入口 4—燃烧室出口.

e—发动机出口

$$\therefore \frac{T_{t4}}{T_{t3}} \bigg|_{M_4=1} = \frac{T_t^*}{T_{t3}} = f(M_3) = 1.53$$

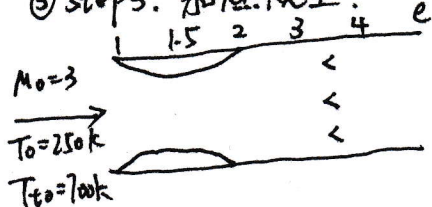
$$\therefore T_{t4} = 1070K.$$

$$\therefore \frac{P_e}{P_0} = 5.66, \frac{T_e}{T_0} = 3.5667, \frac{V_e}{V_0} = \frac{M_e C_e}{M_0 C_0}$$

$$\therefore C_T = 0.$$

加入了热量 (more) 仍无推力, 此时能量全被废气带走了.

③ step 3. 加燃烧室.



对3-4截面, 流量守恒.

$$\dot{m} = K \frac{P_{t3} A_3}{\sqrt{T_{t3}}} \dot{q}(M_3) = K \frac{P_{t4}}{\sqrt{T_{t4}}} \dot{q}(M_4) A_4$$

$$\therefore T_{t3} = T_{t0}, P_{t0} = P_{t3}, M_3 = 3.0, A_3 = A_4.$$

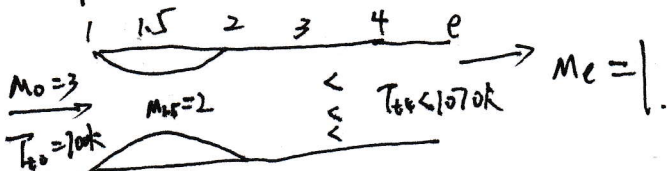
$$2-e \text{ 为等直管, 故 } \frac{P_0}{\sqrt{T_0}} \dot{q}(M_0) = \frac{P_e}{\sqrt{T_{te}}} \dot{q}(M_e)$$

无推力产生.

④ step 4. 相对第3步进一步加燃料, 从而释放

更多热量, 使气流由 $M_3=3$ 降到 $M_e=1$.

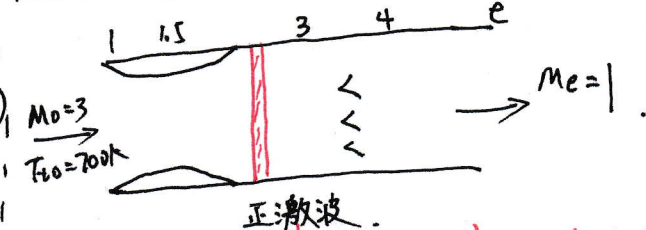
即放热致使超音速气流达到热壅塞状态.



$$\therefore \frac{P_{t0}}{\sqrt{T_{t0}}} \dot{q}(3.0) = \frac{P_{t4}}{\sqrt{T_{t4}}} \dot{q}(M_4)$$

$$= \frac{M_e \sqrt{\gamma R T_e}}{M_0 \sqrt{\gamma R T_0}} = 0.6295$$

⑤ step 5. 再继续增大燃量, 此时会使燃烧室入口前形成正激波. 减速到亚音速



[正激波是因为瑞利流动, $Ma>1$ 时, 再加热使 Ma 趋于1, 再加热会产生正激波]

$$\frac{P_{t2}}{P_{t0}} = 0.3285 \text{ (正激波损失)}$$

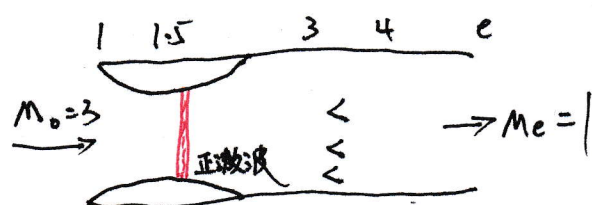
$$\frac{P_{t4}}{P_{t3}} = \frac{P_{t0}^*}{P_{t3}} = 0.889$$

$$\therefore \frac{P_{t0}}{P_{t0}} = 0.292 \Rightarrow \frac{P_e}{P_0} = 5.666.$$

$$\frac{T_e}{T_0} = 3.5667, \frac{V_e}{V_0} = 0.6295.$$

$$C_T = 0 \text{ 仍无推力.}$$

⑥ step 6. 再进一步加热 (加入燃料).



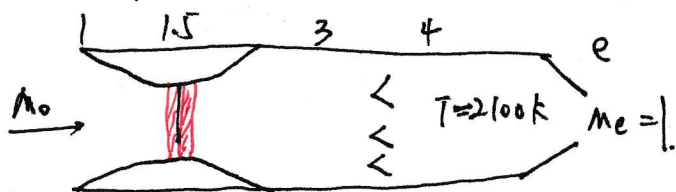
正激波会被推动到喉道附近.

$$\frac{P_{te}}{P_{t0}} = 2(M_0) \sqrt{\frac{T_{te}}{T_{t0}}} = 0.409$$

$$\frac{P_e}{P_0} = 7.94, \frac{T_e}{T_0} = 7 \Rightarrow \frac{V_e}{V_0} = \frac{M_e}{M_0} \sqrt{\frac{T_e}{T_0}} = 0.882.$$

$\therefore C_T = 5.45$!!! 在连接着3次加入燃料后, 终于产生推力.

⑦ step 7. 添加喷管, 使激波推到喉道

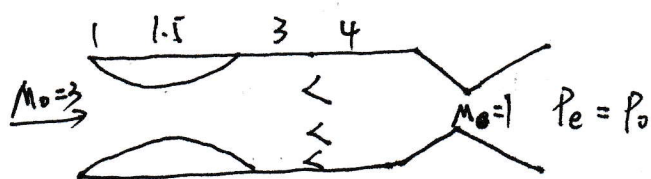


$$M_{1.5} = M_e = 1.$$

$$\frac{P_{t0} A_{1.5}}{\sqrt{T_{t0}}} = \frac{P_{te} A_e}{\sqrt{T_{te}}} \Rightarrow \frac{A_e}{A_{1.5}} = \sqrt{\frac{T_e}{T_{1.5}}} = 1.73.$$

$$\frac{P_e}{P_0} = 19.41, \frac{T_e}{T_0} = 7, \frac{V_e}{V_0} = 0.882. C_T = 6.034. \text{推力继续增大.}$$

⑧ step 8. 再加个扩张段.



$$\frac{P_e}{P_0} = 1, \frac{T_e}{T_0} = \frac{T_{te}}{T_{t0}} = 3.$$

$$\frac{V_e}{V_0} = 1.732 \quad C_T = 9.22. \text{推力又变大了.}$$