ESCOAMENTO UNIDIMENSIONAL

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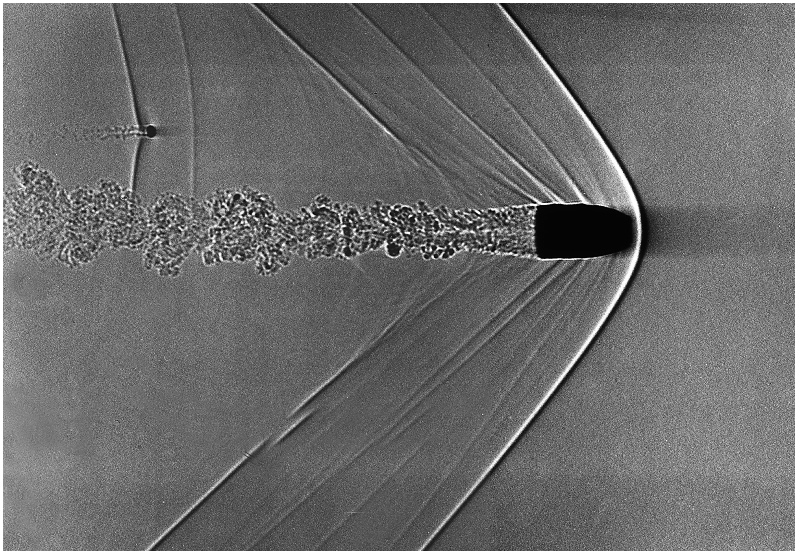
CHOQUE NORMAL



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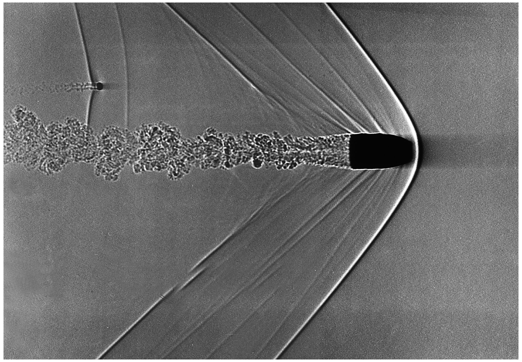
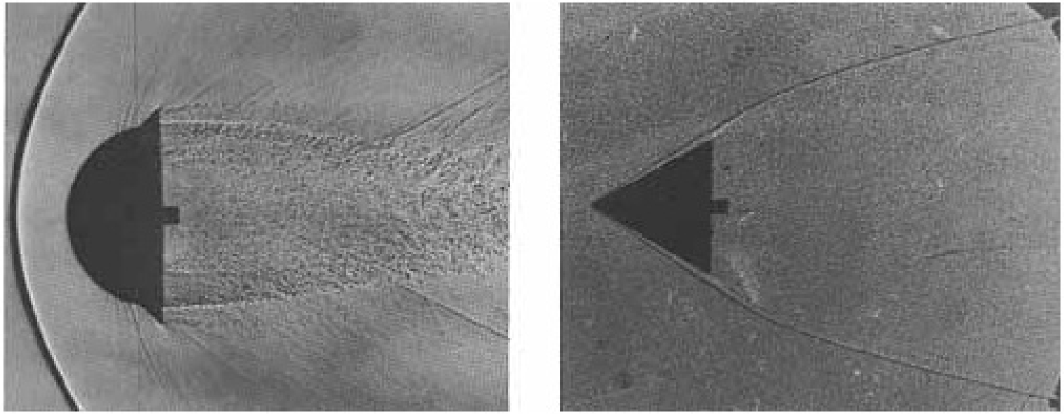


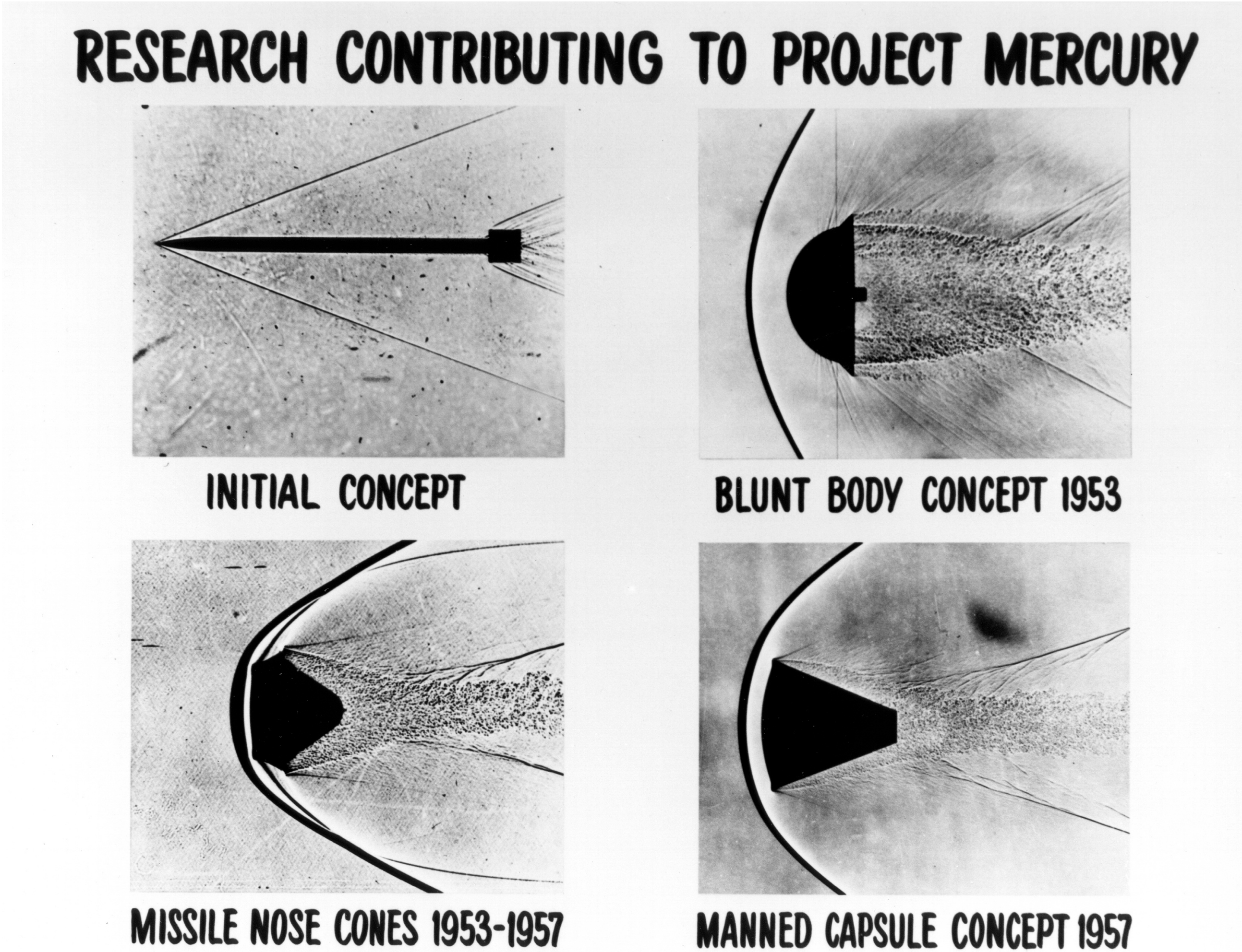
*O que é choque normal
*Hipóteses
*Equações para propriedades depois do choque em função de Mach antes do choque

Choque em arco vs Oblíquo



https://www.hq.nasa.gov/office/pao/History/SP-440/ch6-2.htm

A forte onda produzida pelo corpo rombudo dissipa energia do escoamento reduzindo o aquecimento local do corpo



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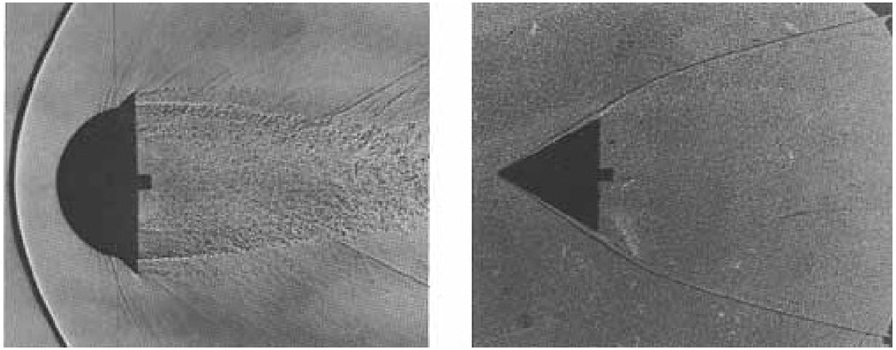

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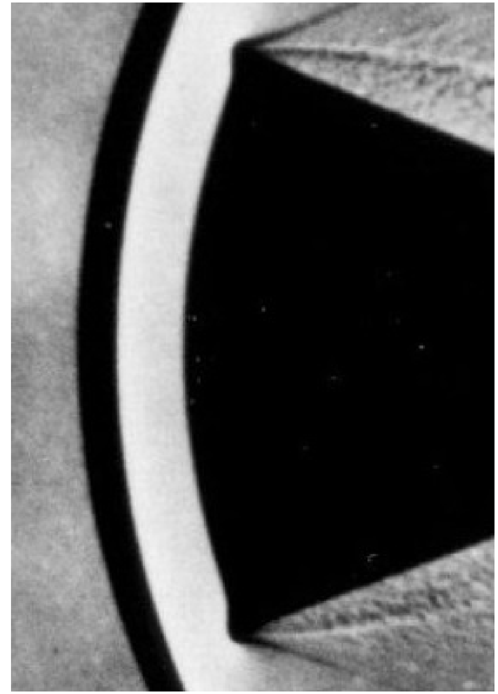


Ondas de choque são descontinuidades no escoamento

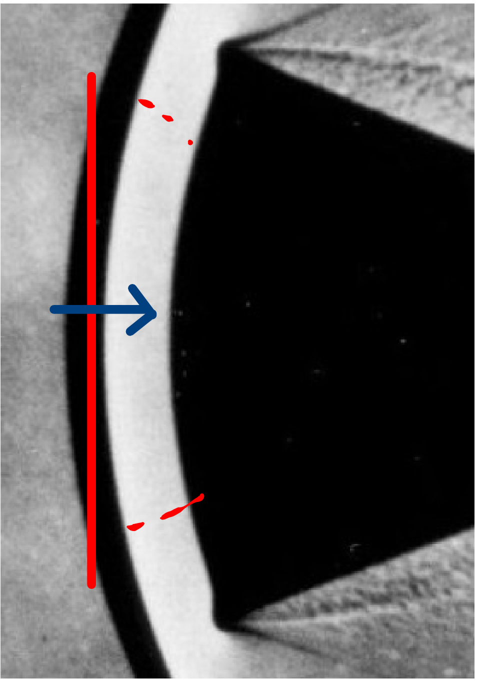
* Propriedades diferentes antes e depois do choque
* Fluido contínuo antes e depois do choque

Região Fina com elevados gradientes de Velocidade e Temperatura

$\nabla u \to \tau = \mu \frac{du}{dy}$ $\qquad$ $\nabla T \to \vec{q} = -kA\nabla T$

Equações Governantes: Choque Normal

Hipótesis do modelo



*Onda de choque é perpendicular ao escoamento

*Choque é uma região muito fina (~10^{-5} cm para ar)

*Propriedades mudam abruptamente

*Sem troca de calor conforme o escoamento atravessa o choque

*Escoamento Unidimensional

*Regime Permanente

*Gás ideal

*Forças de Corpo desprezíveis

*Forças de superfície -> Pressão
(desprezar efeitos viscosos antes e depois do choque)

Equações Governantes

Hipotesis do modelo

*Onda de choque é perpendicular ao escoamento
*Choque é uma região muito fina (~10^{-5} cm para ar)
*Propriedades mudam abruptamente
*Sem troca de calor conforme o escoamento atravessa o choque
*Escoamento Unidimensional
*Regime Permanente
*Gás ideal
*Forças de Corpo desprezíveis
*Forças de superfície -> Pressão (desprezar efeitos viscosos) antes e depois do choque

$$\left.\frac{Dm}{Dt}\right|_s = \frac{\partial}{\partial t}\int_{VC} \rho \, d\forall + \int_{SC} \rho \, \vec{V} \cdot d\vec{A} \quad \Rightarrow \quad \rho_1 V_1 = \rho_2 V_2$$

$$\left.\frac{D(m.\vec{V})}{Dt}\right|_s = \frac{\partial}{\partial t}\int_{VC} \rho \vec{V} \, d\forall + \int_{SC} (\rho \vec{V} \cdot d\vec{A})\, \vec{V} = \sum \vec{F}_s \quad \Rightarrow \quad P_1 + \rho_1 V_1^2 = P_2 + \rho_2 V_2^2$$

$$\left.\frac{DE}{Dt}\right|_s = \frac{\partial}{\partial t}\int_{VC} e \, \rho \, d\forall + \int_{SC} e \cdot (\rho \vec{V} \cdot d\vec{A}) = \dot{Q} + \dot{W} \quad \Rightarrow \quad h_1 + \frac{V_1^2}{2} = h_2 + \frac{V_2^2}{2}$$

FORMAS ALTERNATIVAS DA EQ. ENERGIA

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$$h_1 + \frac{V_1^2}{2} = h_2 + \frac{V_2^2}{2}$$

p/ gás ideal : $h = c_p \cdot T$

$$c_p T_1 + \frac{V_1^2}{2} = c_p T_2 + \frac{V_2^2}{2}$$

$$R = c_p - c_v \Rightarrow \frac{R}{c_p} = \frac{c_p}{c_p} - \frac{c_v}{c_p} \Rightarrow \frac{R}{c_p} = 1 - \frac{1}{K} \Rightarrow \frac{R}{c_p} = \frac{K-1}{K} \Rightarrow c_p = \frac{KR}{K-1}$$

Logo: $\left(\frac{KR}{K-1} T_1\right) + \frac{V_1^2}{2} = \left(\frac{KR}{K-1} T_2\right) + \frac{V_2^2}{2}$

$$\frac{C_1^2}{K-1} + \frac{V_1^2}{2} = \frac{C_2^2}{K-1} + \frac{V_2^2}{2}$$

$$\frac{c_1^2}{k-1} + \frac{V_1^2}{2} = \frac{c_2^2}{k-1} + \frac{V_2^2}{2} = \frac{c^2}{k-1} + \frac{V^2}{2}$$

Associar com condição crítica: M = 1

$c^* = \sqrt{kRT^*}$:

$$\frac{c^2}{k-1} + \frac{V^2}{2} = \frac{c^{*2}}{k-1} + \frac{c^{*2}}{2}$$

$$\frac{c^2}{k-1} + \frac{V^2}{2} = \frac{2c^{*2} + kc^{*2} - c^{*2}}{2(k-1)}$$

$$\boxed{\frac{c^2}{k-1} + \frac{V^2}{2} = \frac{c^{*2}(k+1)}{2(k-1)}}$$

Dado c e V, podemos calcular c*: velocidade associada ao ponto em análise

$$\frac{C^2}{k-1} + \frac{V^2}{2} = \frac{C^{*2}(k+1)}{2(k-1)}$$

$$\frac{\left(\frac{C}{V}\right)^2}{k-1} + \frac{1}{2} = \left(\frac{C^*}{V}\right)^2 \frac{1}{2}\frac{(k+1)}{(k-1)}$$

$$M^* = \frac{V}{C^*} = \frac{V}{\sqrt{kRT^*}} \neq 1 \;!!!$$

$$\frac{\frac{1}{M^2}}{k-1} + \frac{1}{2} = \frac{1}{M^{*2}}\frac{1}{2}\frac{(k+1)}{(k-1)}$$

$$\frac{1}{M^{*2}} = \frac{2(k-1)}{(k+1)} \cdot \frac{1}{(k-1)}\frac{1}{M^2} + \frac{1}{2} \cdot \frac{2(k-1)}{(k+1)}$$

$\rightsquigarrow$

$$\frac{1}{M^{*2}} = \frac{2(k-1)}{(k+1)} \cdot \frac{1}{(k-1)} \frac{1}{M^2} + \frac{1}{2} \cdot \frac{2(k-1)}{(k+1)}$$

$$\frac{1}{M^{*2}} = \frac{2}{M^2(k+1)} + \frac{(k-1)}{(k+1)}$$

$$\frac{1}{M^{*2}} = \frac{2 + M^2(k-1)}{M^2(k+1)}$$

$$M^{*2} = \frac{M^2(k+1)}{2 + M^2(k-1)}$$

p/ $M = 1 \rightarrow M^* = 1$

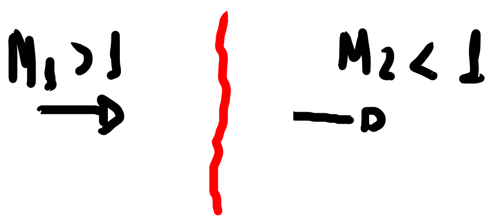
p/ $M < 1 \rightarrow M^* < 1$

p/ $M > 1 \rightarrow M^* > 1$

p/ $M \rightarrow \infty \rightarrow M^* \rightarrow \sqrt{\frac{k+1}{k-1}}$

Equações para Choque Normal

- Onda de choque é perpendicular ao escoamento
- Choque é uma região muito fina ($\sim 10^{-5}$ cm p/ ar)
- Propriedades mudam abruptamente
- Sem troca de calor conforme o escoamento "atravessa" o choque



CONTINUIDADE: $\rho_1 V_1 = \rho_2 V_2$

EQ DO MOMENTO: $p_1 + \rho_1 V_1^2 = p_2 + \rho_2 V_2^2$

EQ ENERGIA $h_1 + \frac{V_1^2}{2} = h_2 + \frac{V_2^2}{2}$

p/ gás perfeito: $p = \rho R T$

$h = c_p \cdot T$

A Relação de Prandtl

$$P_1 + \rho_1 V_1^2 = P_2 + \rho_2 V_2^2$$

$\div\ \rho . V \qquad (\rho_1 V_1 = \rho_2 V_2)$

$$\frac{P_1}{\rho_1 V_1} + \frac{\rho_1 V_1^2}{\rho_1 V_1} = \frac{P_2}{\rho_2 V_2} + \frac{\rho_2 V_2^2}{\rho_2 V_2}$$

$$\frac{P_1}{\rho_1 V_1} + V_1 = \frac{P_2}{\rho_2 V_2} + V_2$$

MAS $C^2 = kRT = k\frac{P}{\rho} \Rightarrow \frac{P}{\rho} = \frac{c^2}{k}$

$$\frac{C_1^2}{k V_1} + V_1 = \frac{C_2^2}{k V_2} + V_2$$

$$\frac{C_1^2}{kV_1} - \frac{C_2^2}{kV_2} = V_2 - V_1$$

$$\boxed{\frac{C^2}{k-1} + \frac{V^2}{2} = \frac{C^{*2}(k+1)}{2(k-1)}} \rightsquigarrow C^2 = \frac{(k+1)}{2} C^{*2} - \frac{(k-1)}{2} V^2$$

$$\left[\frac{(k+1)}{2}\frac{C_1^{*2}}{k.V_1} - \frac{(k-1)}{2}\frac{V_1^2}{k.V_1}\right] - \left[\frac{(k+1)}{2}\frac{C_2^{*2}}{k.V_2} - \frac{(k-1)}{2}\frac{V_2^2}{k.V_2}\right] = V_2 - V_1$$

MAS $C_1^* = C_2^*$ (ADIABÁTICO) $\rightarrow M = 1 \Rightarrow T = T^*$

$$\frac{(k+1)}{2}\frac{C^{*2}}{kV_1} - \frac{(k-1)}{2k}V_1 - \frac{(k+1)}{2}\frac{C^{*2}}{kV_2} + \frac{(k-1)}{2k}V_2 = V_2 - V_1$$

$$\frac{k+1}{2}\frac{C^{*2}}{k}\left(\frac{1}{V_1} - \frac{1}{V_2}\right) + \frac{(k-1)}{2k}(V_2 - V_1) = V_2 - V_1 \rightsquigarrow$$

$$\frac{k+1}{2}\frac{C^{*2}}{k}\left(\frac{1}{V_1}-\frac{1}{V_2}\right)+\frac{(k-1)}{2k}(V_2-V_1)=V_2-V_1$$

$$\frac{k+1}{2}\frac{C^{*2}}{k}\left(\frac{V_2-V_1}{V_1V_2}\right)=(V_2-V_1)\left[1-\frac{(k-1)}{2k}\right]$$

$$\frac{k+1}{2}\frac{C^{*2}}{k}=V_1V_2\left[\frac{2k-k+1}{2k}\right]$$

$$\frac{k+1}{2}\frac{C^{*2}}{k}=V_1V_2\left[\frac{k+1}{2k}\right]$$

$$\boxed{C^{*2}=V_1 . V_2}$$

RELAÇÃO DE PRANDTL

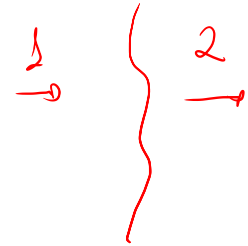
$$C^{*2} = V_1 \cdot V_2$$

$$C^* \cdot C^* = V_1 \cdot V_2$$

$$1 = \frac{V_1}{C^*} \cdot \frac{V_2}{C^*}$$

$$1 = M_1^* \cdot M_2^*$$

$$M_2^* = \frac{1}{M_1^*}$$



$$M_1 > 1 \Rightarrow M_1^* > 1$$

$$M_2^* < 1 \Rightarrow M_2 < 1$$

$$M_2^* = \frac{1}{M_1^*}$$

$$M^{*2} = \frac{M^2(k+1)}{2+M^2(k-1)}$$

$$\frac{M_2^2(k+1)}{2+M_2^2(k-1)} = \frac{2+M_1^2(k-1)}{M_1^2(k+1)}$$

$$\frac{2+M_2^2(k-1)}{M_2^2(k+1)} = \frac{M_1^2(k+1)}{2+M_1^2(k-1)}$$

$$\left(\frac{\frac{2}{M_2^2}+(k-1)}{(k+1)}\right)\frac{M_2^2}{M_2^2} = \frac{M_1^2(k+1)}{2+M_1^2(k-1)}$$

$$\left(\frac{\frac{2}{M_2^2} + (k-1)}{(k+1)}\right)\cancel{\frac{M_2^2}{M_2^2}} = \frac{M_1^2(k+1)}{2 + M_1^2(k-1)}$$

$$\frac{2}{M_2^2} + (k-1) = \frac{M_1^2(k+1)^2}{2 + M_1^2(k-1)}$$

$$\frac{2}{M_2^2} = \frac{M_1^2(k+1)^2}{2 + M_1^2(k-1)} - (k-1)$$

$$\frac{2}{M_2^2} = \frac{M_1^2(k+1)^2 - (k-1)(2 + M_1^2(k-1))}{2 + M_1^2(k-1)}$$

$$\frac{2}{M_2^2} = \frac{M_1^2(k^2 + 2k + 1) - [2(k-1) + (k-1)^2 M_1^2]}{2 + M_1^2(k-1)}$$

$$\frac{2}{M_2^2} = \frac{M_1^2\left(k^2+2k+1\right) - \left[2(k-1) + (k-1)^2 M_1^2\right]}{2 + M_1^2(k-1)}$$

$$\frac{2}{M_2^2} = \frac{M_1^2 k^2 + 2k M_1^2 + M_1^2 - \left[2k - 2 + k^2 M_1^2 - 2k M_1^2 + M_1^2\right]}{2 + M_1^2(k-1)}$$

$$\frac{2}{M_2^2} = \frac{\cancel{M_1^2 k^2} + 2k M_1^2 + \cancel{M_1^2} - 2k + 2 - \cancel{k^2 M_1^2} + 2k M_1^2 - \cancel{M_1^2}}{2 + M_1^2(k-1)}$$

$$\frac{2}{M_2^2} = \frac{4k M_1^2 - 2k + 2}{2 + M_1^2(k-1)}$$

$$M_2^2 = \frac{2 + M_1^2(k-1)}{2k M_1^2 - k + 1}$$

$$\boxed{M_2^2 = \frac{1 + M_1^2 \frac{(k-1)}{2}}{k M_1^2 - \frac{(k-1)}{2}}}$$

Resumo:

$$M_2^* = \frac{1}{M_1^*}$$

$$M^{*2} = \frac{M^2(k+1)}{2+M^2(k-1)}$$

$$\frac{M_2^2(k+1)}{2+M_2^2(k-1)} = \frac{2+M_1^2(k-1)}{M_1^2(k+1)}$$

$$M_2^2 = \frac{1+M_1^2\frac{(k-1)}{2}}{kM_1^2-\frac{(k-1)}{2}}$$

Mach após o choque é função do Mach antes do choque !!!

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$$M_2^2 = \frac{1 + M_1^2 \frac{(k-1)}{2}}{k M_1^2 - \frac{(k-1)}{2}}$$

Si $M_1 \to \infty \Rightarrow M_2 \to \sqrt{\frac{(k-1)}{2k}}$

p/ Ar $M_2 \to 0,378$

Mach antes do choque é um parâmetro importante que dita as propriedades após o choque !!!

OUTRAS EQUAÇÕES ENVOLVENDO M1: massas específicas

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$$\rho_1 V_1 = \rho_2 V_2 \rightarrow \frac{\rho_2}{\rho_1} = \frac{V_1}{V_2}$$

$$c^{*2} = V_1 \cdot V_2 \rightarrow \frac{\rho_2}{\rho_1} = \frac{V_1}{\left(\frac{c^{*2}}{V_1}\right)}$$

$$\frac{\rho_2}{\rho_1} = \frac{V_1^2}{c^{*2}} = M_1^{*2} = \frac{(k+1)\,M_1^2}{2+(k-1)\,M_1^2}$$

$$\boxed{\frac{\rho_2}{\rho_1} = \frac{V_1}{V_2} = \frac{(k+1)\,M_1^2}{2+(k-1)\,M_1^2}}$$

OUTRAS EQUAÇÕES ENVOLVENDO M1: pressões

Eq. Momento

$$P_1 + \rho_1 V_1^2 = P_2 + \rho_2 V_2^2$$

$$P_2 - P_1 = \rho_1 V_1^2 - \rho_2 V_2^2$$

$$P_2 - P_1 = \rho_1 V_1 \, V_1 - \rho_2 V_2 \, V_2 \qquad \rho_1 V_1 = \rho_2 V_2$$

$$P_2 - P_1 = \rho_1 V_1 (V_1 - V_2)$$

$$P_2 - P_1 = \rho_1 V_1^2 \left(1 - \frac{V_2}{V_1}\right)$$

$$\frac{P_2 - P_1}{P_1} = \frac{\rho_1 V_1^2}{P_1}\left(1 - \frac{V_2}{V_1}\right) \qquad c^2 = \frac{kP}{\rho} \rightarrow \frac{P}{\rho} = \frac{c^2}{k}$$

$$\frac{P_2 - P_1}{P_1} = k \frac{V_1^2}{c_1^2}\left(1 - \frac{V_2}{V_1}\right)$$

$$\frac{P_2 - P_1}{P_1} = k \frac{V_1^2}{C_1^2}\left(1 - \frac{V_2}{V_1}\right)$$

$$\frac{P_2}{P_1} - \frac{P_1}{P_1} = k M_1^2 \left(1 - \frac{V_2}{V_1}\right)$$

$$\frac{\rho_2}{\rho_1} = \frac{V_1}{V_2} = \frac{(k+1) M_1^2}{2 + (k-1) M_1^2}$$

$$\frac{P_2}{P_1} - 1 = k M_1^2 \left[1 - \frac{2 + (k-1) M_1^2}{(k+1) M_1^2}\right]$$

$$\frac{P_2}{P_1} = 1 + k M_1^2 \left[1 - \frac{2 + (k-1) M_1^2}{(k+1) M_1^2}\right]$$

$$\frac{P_2}{P_1} = 1 + k M_1^2 \left[\frac{(k+1) M_1^2 - 2 - (k-1) M_1^2}{(k+1) M_1^2}\right]$$

$$\frac{P_2}{P_1} = 1 + kM_1^2\left[\frac{(k+1)M_1^2 - 2 - (k-1)M_1^2}{(k+1)M_1^2}\right]$$

$$\frac{P_2}{P_1} = 1 + k\left[\frac{kM_1^2 + M_1^2 - 2 - kM_1^2 + M_1^2}{k+1}\right]$$

$$\frac{P_2}{P_1} = 1 + k\left[\frac{2M_1^2 - 2}{k+1}\right]$$

$$\frac{P_2}{P_1} = 1 + \frac{2k}{(k+1)}\left(M_1^2 - 1\right)$$

$$\frac{P_2}{P_1} = F(M_1)$$

$$\frac{p_2}{p_1} = 1 + \frac{2k}{k+1}\left(M_1^2 - 1\right)$$

$$\frac{\rho_2}{\rho_1} = \frac{V_1}{V_2} = \frac{(k+1)M_1^2}{2 + (k-1)M_1^2}$$

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$$p = \rho R T \Rightarrow \frac{T_2}{T_1} = \frac{\dfrac{p_2}{R\rho_2}}{\dfrac{p_1}{R\rho_1}} \Rightarrow \frac{T_2}{T_1} = \frac{p_2}{p_1} \cdot \frac{\rho_1}{\rho_2}$$

$$\frac{T_2}{T_1} = \frac{h_2}{h_1} = \left[1 + \frac{2k}{k+1}\left(M_1^2 - 1\right)\right]\left[\frac{2 + (k-1)M_1^2}{(k+1)M_1^2}\right]$$

$$M_2^2 = \frac{1 + M_1^2 \frac{(k-1)}{2}}{k M_1^2 - \frac{(k-1)}{2}}$$

$$\frac{P_2}{P_1} = 1 + \frac{2k}{k+1}\left(M_1^2 - 1\right)$$

$$\frac{\rho_2}{\rho_1} = \frac{V_1}{V_2} = \frac{(k+1) M_1^2}{2 + (k-1) M_1^2}$$

$$\frac{T_2}{T_1} = \frac{h_2}{h_1} = \left[1 + \frac{2k}{k+1}\left(M_1^2 - 1\right)\right]\left[\frac{2 + (k-1) M_1^2}{(k+1) M_1^2}\right] = \frac{P_2}{P_1} \cdot \left(\frac{\rho_2}{\rho_1}\right)^{-1}$$

Conhecendo M_1

M_1 → M_2, $\frac{\rho_2}{\rho_1}$, $\frac{P_2}{P_1}$, $\frac{T_2}{T_1}$

* MAS → NÃO há restrição para M_1

$$s_2 - s_1 = c_p \ln\left(\frac{T_2}{T_1}\right) - R \ln\left(\frac{P_2}{P_1}\right)$$

$$\frac{T_2}{T_1} = \frac{h_2}{h_1} = \left[1 + \frac{2k}{k+1}\left(M_1^2 - 1\right)\right]\left[\frac{2 + (k-1)M_1^2}{(k+1)M_1^2}\right]$$

$$\frac{P_2}{P_1} = 1 + \frac{2k}{k+1}\left(M_1^2 - 1\right)$$

$$\therefore \; s_2 - s_1 = F(M_1)$$

Se $M_1 < 1 \rightarrow s_2 - s_1 < 0$

Se $M_1 = 1 \rightarrow s_2 - s_1 = 0$

Se $M_1 > 1 \rightarrow s_2 - s_1 > 0$

Para Choque: $M_1 \geq 1$

$M_2 \leq 1$; $\frac{\rho_2}{\rho_1} \geq 1$; $\frac{P_2}{P_1} \geq 1$; $\frac{T_2}{T_1} \geq 1$

Propriedades de estagnação

$M_1 > 1$

T_1, P_1, ρ_1, s_1 $\quad$ $T_{01}, P_{01}, \rho_{01}, s_1$

$M_2 < 1$

T_2, P_2, ρ_2, s_2 $\quad$ $T_{02}, P_{02}, \rho_{02}, s_2$

$$c_p T_1 + \frac{V_1^2}{2} = c_p T_{01} = c_p T_2 + \frac{V_2^2}{2} = c_p T_{02}$$

$$c_p T_{01} = c_p T_{02}$$

$$T_{01} = T_{02}$$

$$P_{02}/P_{01}$$

$$\frac{P_2}{P_1} = 1 + \frac{2k}{k+1}\left(M_1^2 - 1\right)$$

$$M_2^2 = \frac{1 + M_1^2 \frac{(k-1)}{2}}{k M_1^2 - \frac{(k-1)}{2}}$$

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$$\frac{P_{02}}{P_2} = \left(1 + \frac{k-1}{2} M_2^2\right)^{k/k-1}$$

$$\frac{P_{01}}{P_1} = \left(1 + \frac{k-1}{2} M_1^2\right)^{k/k-1}$$

$$\frac{P_{02}}{P_{01}} = \frac{P_2 \left(1 + \frac{k-1}{2} M_2^2\right)^{k/k-1}}{P_1 \left(1 + \frac{k-1}{2} M_1^2\right)^{k/k-1}}$$

$$\frac{P_{02}}{P_{01}} = \left[1 + \frac{2k}{k+1}\left(M_1^2 - 1\right)\right] \frac{\left(1 + \frac{k-1}{2} M_2^2\right)^{k/k-1}}{\left(1 + \frac{k-1}{2} M_1^2\right)^{k/k-1}}$$

$$p_{02}/p_1$$

$$\frac{p_{01}}{p_1} = \left(1 + \frac{k-1}{2} M_1^2\right)^{k/k-1} \Rightarrow p_1 = \frac{p_{01}}{\left(1 + \frac{k-1}{2} M_1^2\right)^{k/k-1}}$$

$$\frac{p_{02}}{p_{01}} = \left[1 + \frac{2k}{k+1}\left(M_1^2 - 1\right)\right] \frac{\left(1 + \frac{k-1}{2} M_2^2\right)^{k/k-1}}{\left(1 + \frac{k-1}{2} M_1^2\right)^{k/k-1}}$$

$$\frac{p_{02}}{p_1} = \left[1 + \frac{2k}{k+1}\left(M_1^2 - 1\right)\right] \frac{\;\frac{\left(1 + \frac{k-1}{2} M_2^2\right)^{k/k-1}}{\left(1 + \frac{k-1}{2} M_1^2\right)^{k/k-1}}\;}{\left(\left(1 + \frac{k-1}{2} M_1^2\right)^{k/k-1}\right)}$$

$$\boxed{\frac{p_{02}}{p_1} = \left[1 + \frac{2k}{k+1}\left(M_1^2 - 1\right)\right] \left(1 + \frac{k-1}{2} M_2^2\right)^{k/k-1}}$$

$$T_{02} = T_{01} = F(T_1, M_1)$$

$$P_{02} = F(P_1, M_1)$$

$$P = \rho R T \Rightarrow \rho_{02} = \frac{P_{02}}{R T_{02}} = F(T_1, P_1, M_1)$$

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Tabela 1.2 – Tabela para Choque Normal. $k = 1,4$

M_1	M_2	$\frac{\rho_2}{\rho_1}$	$\frac{P_2}{P_1}$	$\frac{T_2}{T_1}$	ds	$\frac{P_{o2}}{P_{o1}}$	$\frac{P_{o2}}{P_1}$
1,00	1,000000	1,000000	1,000000	1,000000	0,000000	1,000000	1,892929
1,02	0,980519	1,033441	1,047133	1,013249	0,000003	0,999990	1,937897
1,04	0,962025	1,067088	1,095200	1,026345	0,000022	0,999923	1,984423
1,06	0,944445	1,100921	1,144200	1,039312	0,000072	0,999751	2,032453
1,08	0,927713	1,134925	1,194133	1,052170	0,000163	0,999431	2,081942
1,10	0,911770	1,169082	1,245000	1,064938	0,000308	0,998928	2,132847
1,12	0,896563	1,203377	1,296800	1,077634	0,000513	0,998213	2,185134
1,14	0,882042	1,237793	1,349533	1,090274	0,000787	0,997261	2,238769
1,16	0,868162	1,272315	1,403200	1,102872	0,001135	0,996052	2,293725
1,18	0,854884	1,306927	1,457800	1,115441	0,001563	0,994569	2,349977
1,20	0,842170	1,341615	1,513333	1,127994	0,002074	0,992798	2,407502
1,22	0,829986	1,376364	1,569800	1,140541	0,002673	0,990731	2,466280
1,24	0,818301	1,411160	1,627200	1,153094	0,003361	0,988359	2,526294
1,26	0,807085	1,445989	1,685533	1,165661	0,004140	0,985677	2,587527
1,28	0,796312	1,480839	1,744800	1,178251	0,005014	0,982682	2,649964
1,30	0,785957	1,515695	1,805000	1,190873	0,005982	0,979374	2,713594
1,32	0,775997	1,550546	1,866133	1,203533	0,007045	0,975752	2,778403
1,34	0,766412	1,585379	1,928200	1,216239	0,008204	0,971819	2,844381
1,36	0,757181	1,620182	1,991200	1,228998	0,009459	0,967579	2,911518
1,38	0,748286	1,654945	2,055133	1,241814	0,010810	0,963035	2,979806
1,40	0,739709	1,689655	2,120000	1,254694	0,012256	0,958194	3,049235
1,42	0,731436	1,724303	2,185800	1,267643	0,013797	0,953063	3,119800
1,44	0,723451	1,758878	2,252533	1,280665	0,015433	0,947648	3,191492
1,46	0,715740	1,793370	2,320200	1,293765	0,017161	0,941958	3,264305
1,48	0,708290	1,827770	2,388800	1,306948	0,018982	0,936001	3,338235
1,50	0,701089	1,862069	2,458333	1,320216	0,020894	0,929787	3,413275
1,52	0,694125	1,896257	2,528800	1,333574	0,022895	0,923324	3,489420
1,54	0,687388	1,930327	2,600200	1,347026	0,024986	0,916624	3,566667
1,56	0,680867	1,964270	2,672533	1,360573	0,027163	0,909697	3,645010
1,58	0,674553	1,998079	2,745800	1,374220	0,029426	0,902552	3,724446
1,60	0,668437	2,031746	2,820000	1,387969	0,031773	0,895200	3,804972
1,62	0,662511	2,065264	2,895133	1,401822	0,034203	0,887653	3,886584
1,64	0,656765	2,098627	2,971200	1,415783	0,036714	0,879921	3,969279
1,66	0,651194	2,131827	3,048200	1,429853	0,039305	0,872014	4,053053
1,68	0,645789	2,164860	3,126133	1,444035	0,041973	0,863944	4,137906
1,70	0,640544	2,197719	3,205000	1,458330	0,044718	0,855721	4,223833
1,72	0,635452	2,230398	3,284800	1,472742	0,047537	0,847356	4,310833
1,74	0,630508	2,262893	3,365533	1,487270	0,050429	0,838860	4,398903
1,76	0,625705	2,295199	3,447200	1,501918	0,053393	0,830242	4,488041
1,78	0,621037	2,327310	3,529800	1,516687	0,056426	0,821513	4,578246
1,80	0,616501	2,359223	3,613333	1,531578	0,059528	0,812684	4,669516
1,82	0,612091	2,390934	3,697800	1,546592	0,062695	0,803763	4,761848
1,84	0,607802	2,422438	3,783200	1,561732	0,065928	0,794761	4,855242
1,86	0,603629	2,453733	3,869533	1,576999	0,069224	0,785686	4,949696
1,88	0,599569	2,484814	3,956800	1,592393	0,072581	0,776549	5,045208
1,90	0,595616	2,515679	4,045000	1,607916	0,075999	0,767357	5,141777
1,92	0,591769	2,546325	4,134133	1,623568	0,079475	0,758119	5,239403
1,94	0,588022	2,576749	4,224200	1,639352	0,083007	0,748844	5,338083
1,96	0,584372	2,606949	4,315200	1,655268	0,086596	0,739540	5,437816
1,98	0,580816	2,636922	4,407133	1,671317	0,090238	0,730214	5,538603

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Tabela 1.2 – *Continuação da página anterior*

M_1	M_2	$\frac{\rho_2}{\rho_1}$	$\frac{P_2}{P_1}$	$\frac{T_2}{T_1}$	ds	$\frac{P_{o2}}{P_{o1}}$	$\frac{P_{o2}}{P_1}$
2,00	0,577350	2,666667	4,500000	1,687500	0,093933	0,720874	5,640441
2,02	0,573972	2,696181	4,593800	1,703817	0,097678	0,711527	5,743330
2,04	0,570679	2,725463	4,688533	1,720271	0,101473	0,702180	5,847268
2,06	0,567467	2,754511	4,784200	1,736860	0,105317	0,692839	5,952256
2,08	0,564334	2,783325	4,880800	1,753586	0,109207	0,683512	6,058292
2,10	0,561277	2,811902	4,978333	1,770450	0,113142	0,674203	6,165375
2,12	0,558294	2,840243	5,076800	1,787453	0,117122	0,664919	6,273505
2,14	0,555383	2,868345	5,176200	1,804594	0,121144	0,655666	6,382681
2,16	0,552541	2,896209	5,276533	1,821876	0,125208	0,646447	6,492903
2,18	0,549766	2,923834	5,377800	1,839297	0,129312	0,637269	6,604169
2,20	0,547056	2,951220	5,480000	1,856860	0,133454	0,628136	6,716480
2,22	0,544409	2,978365	5,583133	1,874563	0,137635	0,619053	6,829835
2,24	0,541822	3,005271	5,687200	1,892409	0,141852	0,610023	6,944232
2,26	0,539295	3,031936	5,792200	1,910396	0,146105	0,601051	7,059673
2,28	0,536825	3,058362	5,898133	1,928527	0,150391	0,592140	7,176155
2,30	0,534411	3,084548	6,005000	1,946801	0,154711	0,583295	7,293680
2,32	0,532051	3,110495	6,112800	1,965218	0,159063	0,574517	7,412245
2,34	0,529743	3,136202	6,221533	1,983779	0,163446	0,565810	7,531852
2,36	0,527486	3,161671	6,331200	2,002485	0,167858	0,557177	7,652499
2,38	0,525278	3,186902	6,441800	2,021336	0,172300	0,548621	7,774187
2,40	0,523118	3,211896	6,553333	2,040332	0,176769	0,540144	7,896914
2,42	0,521004	3,236653	6,665800	2,059473	0,181265	0,531748	8,020681
2,44	0,518936	3,261174	6,779200	2,078760	0,185787	0,523435	8,145487
2,46	0,516911	3,285461	6,893533	2,098194	0,190334	0,515208	8,271331
2,48	0,514929	3,309514	7,008800	2,117773	0,194905	0,507067	8,398214
2,50	0,512989	3,333333	7,125000	2,137500	0,199499	0,499015	8,526136
2,52	0,511089	3,356921	7,242133	2,157374	0,204116	0,491052	8,655095
2,54	0,509228	3,380279	7,360200	2,177394	0,208754	0,483181	8,785092
2,56	0,507406	3,403407	7,479200	2,197563	0,213412	0,475402	8,916127
2,58	0,505620	3,426307	7,599133	2,217879	0,218090	0,467715	9,048199
2,60	0,503871	3,448980	7,720000	2,238343	0,222787	0,460123	9,181308
2,62	0,502157	3,471427	7,841800	2,258956	0,227502	0,452625	9,315453
2,64	0,500477	3,493651	7,964533	2,279717	0,232235	0,445223	9,450636
2,66	0,498830	3,515651	8,088200	2,300626	0,236984	0,437916	9,586854
2,68	0,497216	3,537431	8,212800	2,321685	0,241749	0,430705	9,724109
2,70	0,495634	3,558991	8,338333	2,342892	0,246530	0,423590	9,862399
2,72	0,494082	3,580333	8,464800	2,364249	0,251325	0,416572	10,001726
2,74	0,492560	3,601458	8,592200	2,385756	0,256133	0,409650	10,142088
2,76	0,491068	3,622369	8,720533	2,407412	0,260955	0,402825	10,283485
2,78	0,489604	3,643066	8,849800	2,429218	0,265790	0,396096	10,425918
2,80	0,488167	3,663551	8,980000	2,451173	0,270636	0,389464	10,569386
2,82	0,486758	3,683827	9,111133	2,473279	0,275494	0,382927	10,713888
2,84	0,485376	3,703894	9,243200	2,495536	0,280363	0,376486	10,859426
2,86	0,484019	3,723755	9,376200	2,517942	0,285241	0,370141	11,005998
2,88	0,482687	3,743411	9,510133	2,540500	0,290130	0,363890	11,153605
2,90	0,481380	3,762864	9,645000	2,563207	0,295027	0,357733	11,302246
2,92	0,480096	3,782115	9,780800	2,586066	0,299933	0,351670	11,451922
2,94	0,478836	3,801167	9,917533	2,609076	0,304846	0,345701	11,602632
2,96	0,477599	3,820021	10,055200	2,632237	0,309767	0,339823	11,754375
2,98	0,476384	3,838679	10,193800	2,655549	0,314696	0,334038	11,907153
3,00	0,475191	3,857143	10,333333	2,679012	0,319630	0,328344	12,060965

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Tabela 1.2 – *Continuação da página anterior*

M_1	M_2	$\frac{\rho_2}{\rho_1}$	$\frac{P_2}{P_1}$	$\frac{T_2}{T_1}$	ds	$\frac{P_{o2}}{P_{o1}}$	$\frac{P_{o2}}{P_1}$
4,04	0,433899	4,592976	18,875200	4,109579	0,576518	0,134153	21,482015
4,06	0,433380	4,603586	19,064200	4,141163	0,581349	0,131914	21,690528
4,08	0,432868	4,614088	19,254133	4,172901	0,586173	0,129715	21,900073
4,10	0,432363	4,624484	19,445000	4,204793	0,590990	0,127556	22,110649
4,12	0,431865	4,634775	19,636800	4,236840	0,595800	0,125436	22,322256
4,14	0,431373	4,644962	19,829533	4,269041	0,600602	0,123355	22,534894
4,16	0,430888	4,655046	20,023200	4,301397	0,605397	0,121311	22,748563
4,18	0,430410	4,665029	20,217800	4,333907	0,610185	0,119304	22,963263
4,20	0,429938	4,674912	20,413333	4,366571	0,614965	0,117334	23,178994
4,22	0,429472	4,684695	20,609800	4,399390	0,619737	0,115399	23,395756
4,24	0,429012	4,694381	20,807200	4,432363	0,624502	0,113498	23,613548
4,26	0,428559	4,703969	21,005533	4,465491	0,629259	0,111633	23,832372
4,28	0,428111	4,713462	21,204800	4,498774	0,634009	0,109801	24,052227
4,30	0,427669	4,722861	21,405000	4,532211	0,638750	0,108002	24,273113
4,32	0,427233	4,732166	21,606133	4,565802	0,643483	0,106235	24,495029
4,34	0,426803	4,741378	21,808200	4,599548	0,648209	0,104500	24,717976
4,36	0,426378	4,750500	22,011200	4,633449	0,652926	0,102796	24,941955
4,38	0,425959	4,759531	22,215133	4,667505	0,657635	0,101124	25,166964
4,40	0,425545	4,768473	22,420000	4,701715	0,662336	0,099481	25,393004
4,42	0,425136	4,777327	22,625800	4,736080	0,667029	0,097867	25,620074
4,44	0,424732	4,786093	22,832533	4,770599	0,671714	0,096283	25,848176
4,46	0,424334	4,794774	23,040200	4,805273	0,676390	0,094727	26,077308
4,48	0,423940	4,803370	23,248800	4,840102	0,681057	0,093199	26,307471
4,50	0,423552	4,811881	23,458333	4,875086	0,685717	0,091698	26,538665
4,52	0,423168	4,820310	23,668800	4,910224	0,690367	0,090224	26,770890
4,54	0,422789	4,828656	23,880200	4,945517	0,695009	0,088776	27,004145
4,56	0,422415	4,836921	24,092533	4,980965	0,699643	0,087354	27,238431
4,58	0,422045	4,845106	24,305800	5,016568	0,704268	0,085958	27,473748
4,60	0,421680	4,853211	24,520000	5,052325	0,708885	0,084586	27,710095
4,62	0,421319	4,861238	24,735133	5,088237	0,713492	0,083239	27,947473
4,64	0,420963	4,869188	24,951200	5,124304	0,718091	0,081916	28,185882
4,66	0,420611	4,877061	25,168200	5,160526	0,722681	0,080616	28,425322
4,68	0,420263	4,884858	25,386133	5,196903	0,727263	0,079340	28,665792
4,70	0,419920	4,892580	25,605000	5,233435	0,731836	0,078086	28,907292
4,72	0,419581	4,900229	25,824800	5,270121	0,736399	0,076854	29,149824
4,74	0,419245	4,907804	26,045533	5,306963	0,740954	0,075644	29,393386
4,76	0,418914	4,915307	26,267200	5,343959	0,745500	0,074455	29,637978
4,78	0,418586	4,922739	26,489800	5,381110	0,750038	0,073287	29,883602
4,80	0,418263	4,930100	26,713333	5,418416	0,754566	0,072140	30,130255
4,82	0,417943	4,937391	26,937800	5,455877	0,759085	0,071013	30,377940
4,84	0,417627	4,944613	27,163200	5,493493	0,763596	0,069905	30,626655
4,86	0,417315	4,951767	27,389533	5,531264	0,768097	0,068818	30,876400
4,88	0,417006	4,958854	27,616800	5,569190	0,772589	0,067749	31,127176
4,90	0,416701	4,965874	27,845000	5,607271	0,777073	0,066699	31,378983
4,92	0,416400	4,972828	28,074133	5,645507	0,781547	0,065667	31,631820
4,94	0,416101	4,979717	28,304200	5,683898	0,786013	0,064653	31,885688
4,96	0,415807	4,986541	28,535200	5,722443	0,790469	0,063657	32,140586
4,98	0,415515	4,993302	28,767133	5,761144	0,794916	0,062678	32,396515
5,00	0,415227	5,000000	29,000000	5,800000	0,799354	0,061716	32,653474