ESCOAMENTO COMPRESSÍVEL

EXERCÍCIO

CIÊNCIAS TÉRMICAS .com

PROPRIEDADES DE ESTAGNAÇÃO APÓS CHOQUE NORMAL

Um míssel rombudo voa a Mach 2 ao nível do mar. Calcule a temperatura e pressão no nariz do míssil

$$M_2^2 = \frac{1+[\frac{k-1}{2}]M_1^2}{kM_1^2 - \frac{k-1}{2}}$$

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

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

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

$$s_2 - s_1 = -R\ln\frac{P_{o2}}{P_{o1}}$$

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

Formulário

Gráficos

Calculadora Online

$$M_2^2 = \frac{1 + [\frac{k-1}{2}]M_1^2}{kM_1^2 - \frac{k-1}{2}}$$

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

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

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

$$s_2 - s_1 = -R \ln \frac{P_{o2}}{P_{o1}}$$

Tabelas

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

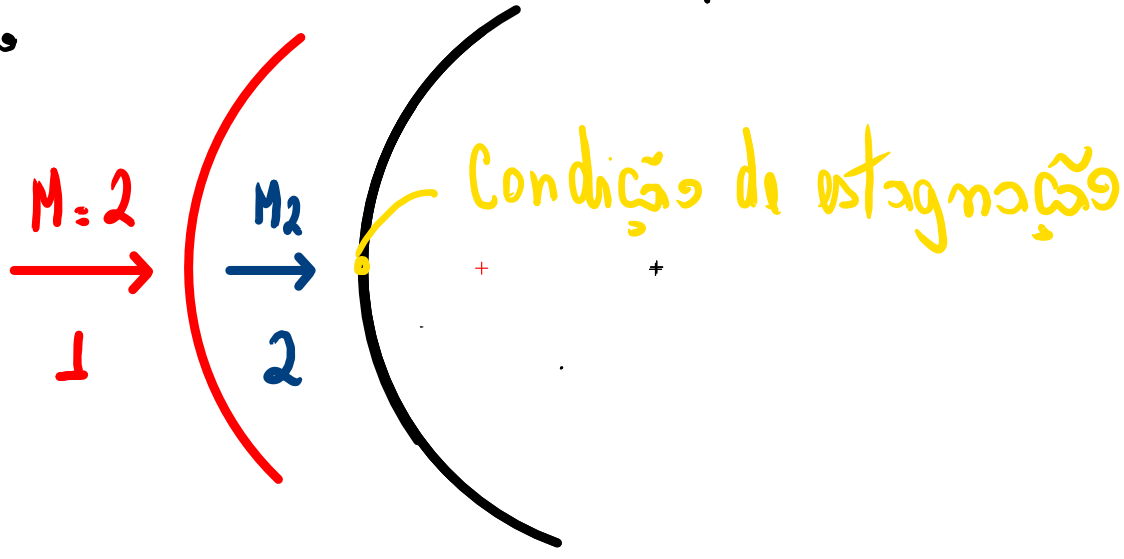
M_1	M_2	$\frac{\rho_2}{\rho_1}$	$\frac{P_2}{P_1}$	$\frac{T_2}{T_1}$	ds	$\frac{P_{o2}}{P_{o1}}$	$\frac{P_{o2}}{P_1}$
1,00	1,000000	1,000000	1,000000	1,000000	0,000000	1,000000	1,892929
1,02	0,980519	1,033441	1,047133	1,013249	0,000003	0,999990	1,937897
1,04	0,962025	1,067088	1,095200	1,026345	0,000022	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

Hipóteses do modelo

- Corpo rombudo → choque in situ
- Regime permanente
- Escoamento unidimensional

} Choque normal

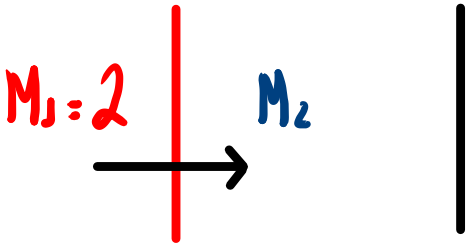
- Desprezando forças de corpo
- Propriedades contínuas antes e depois do choque
- Adiabático



Um míssel rombudo voa a Mach 2 ao nível do mar. Calcule a temperatura e pressão no nariz do míssil

Considerar $T = 15°C = 288,16K$

$P = 101,325\ kPa$



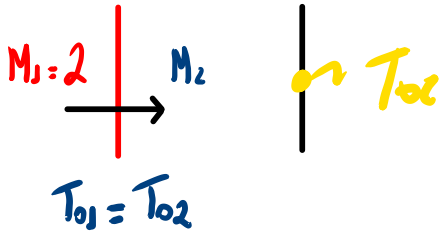
$$h_{o1} = h_1 + \frac{V_1'}{2} = h_2 + \frac{V_2'}{2} = h_{o2}$$

$$c_p T_{o1} = c_p T_{o2}$$

$$T_{o1} = T_{o2}$$

Um míssel rombudo voa a Mach 2 ao nível do mar. Calcule a temperatura e pressão no nariz do míssil

Considerar $T = 15°C = 288,16K$ $P = 101,325\ kPa$



$T_{01} = T_{02}$

$$\frac{T_{01}}{T_1} = 1 + \frac{k-1}{2} M_1^2 \qquad h_0 = h + \frac{V^2}{2}$$

$$\frac{T_{01}}{T_1} = 1 + \frac{1,4-1}{2} \cdot 2^2 = 1,8$$

$$T_{01} = 518,688K = T_{02N}$$

Calculando pelas propriedades após o choque: M_2

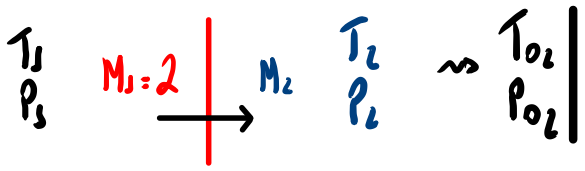
$$M_2^2 = \frac{1+[\frac{k-1}{2}]M_1^2}{kM_1^2 - \frac{k-1}{2}}$$

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

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

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

$$s_2 - s_1 = -R\ln\frac{P_{o2}}{P_{o1}}$$



$$M_2^2 = \frac{1 + \left(\frac{1,4-1}{2}\right)\cdot 2^2}{1,4\cdot 2^2 - \frac{1,4-1}{2}}$$

$$M_2 = 0,57735$$

Calculo de P_2

$$M_2^2 = \frac{1 + [\frac{k-1}{2}]M_1^2}{kM_1^2 - \frac{k-1}{2}}$$

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

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

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

$$s_2 - s_1 = -R \ln \frac{P_{o2}}{P_{o1}}$$

$$\frac{P_2}{P_1} = 1 + \frac{2 \times 1,4}{1,4+1}(2^2 - 1)$$

$$\frac{P_2}{P_1} = 4,5 \Rightarrow P_2 = 455,625 kPa$$

Calculo de T_2

$$M_2^2 = \frac{1+[\frac{k-1}{2}]M_1^2}{kM_1^2 - \frac{k-1}{2}}$$

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

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

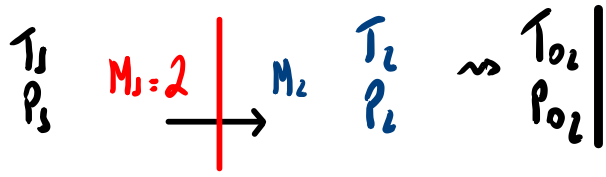
$$\frac{T_2}{T_1} = \frac{h_2}{h_1} = \left[1 + \frac{2k}{k+1}(M_1^2 - 1)\right]\left[\frac{2+(k-1)M_1^2}{(k+1)M_1^2}\right]$$

$$s_2 - s_1 = -R\ln\frac{P_{o2}}{P_{o1}}$$

$$\frac{T_2}{T_1} = 4{,}5\left(\frac{2k\,(1{,}4-1)\,2^2}{(1{,}4+1)\cdot 2^2}\right)$$

$$\frac{T_2}{T_1} = 3{,}6875 \Rightarrow T_2 = 486{,}27\,K$$

Propriedades de Estagnação após o choque



$$M_1 = 2 \rightsquigarrow M_2 = 0{,}57735$$

$$\frac{T_{02}}{T_2} = 1 + \frac{k-1}{2} M_2^2 = 1 + \frac{1{,}4-1}{2} \cdot 0{,}57735^2$$

$$\frac{T_{02}}{T_2} = 1{,}0666 \rightsquigarrow T_{02} = 516{,}688\,K = T_{01}\ !$$

$$\frac{P_{02}}{P_2} = \left(\frac{T_{02}}{T_2}\right)^{k/k-1}$$

$$\frac{P_{02}}{P_2} = 1{,}2534 \rightsquigarrow P_{02} = 511{,}5175\ \text{kPa}$$

TABELAS

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	$\frac{P_{o2}}{P_{o1}}$	$\frac{P_{o2}}{P_1}$
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

$M_1 = 2 \rightsquigarrow M_2 = 0,57735$

$\frac{P_{o2}}{P_1} = 5,640441 \rightsquigarrow P_{o2} = 571,5177\ kPa$ (571,5175)

$\frac{T_2}{T_1} = 1,6875$ (1,6875) $\rightsquigarrow T_2 = 486,27$

TABELAS

$M_2 = 0{,}51735$ $T_2 = 486{,}27$

Tabela 1.1 – Tabela para escoamento Isoentrópico. $k = 1{,}4$

M	$\frac{T_o}{T}$	$\frac{P_o}{P}$	$\frac{\rho_o}{\rho}$
0,00	1,000000000	1,000000000	1,000000000
0,02	1,000080000	1,000280028	1,000200012
0,04	1,000320000	1,001120448	1,000800192
0,06	1,000720000	1,002522269	1,001800972
0,08	1,001280000	1,004487173	1,003203073
0,10	1,002000000	1,007017518	1,005007502
0,12	1,002880000	1,010116340	1,007215559
0,14	1,003920000	1,013787360	1,009828831
0,16	1,005120000	1,018034982	1,012849194
0,18	1,006480000	1,022864304	1,016278817
0,20	1,008000000	1,028281121	1,020120160
0,22	1,009680000	1,034291935	1,024375975
0,24	1,011520000	1,040903957	1,029049309
0,26	1,013520000	1,048125123	1,034143503
0,28	1,015680000	1,055964098	1,039662194
0,30	1,018000000	1,064430286	1,045609318
0,32	1,020480000	1,073533846	1,051989110
0,34	1,023120000	1,083285700	1,058806103
0,36	1,025920000	1,093697545	1,066065136
0,38	1,028880000	1,104781869	1,073771352
0,40	1,032000000	1,116551966	1,081930199
0,42	1,035280000	1,129021948	1,090547435
0,44	1,038720000	1,142206766	1,099629126
0,46	1,042320000	1,156122222	1,109181654
0,48	1,046080000	1,170784991	1,119211715
0,50	1,050000000	1,186212638	1,129726322
0,52	1,054080000	1,202423640	1,140732810
0,54	1,058320000	1,219437404	1,152238835
0,56	1,062720000	1,237274290	1,164252381
0,58	1,067280000	1,255955636	1,176781759
0,60	1,072000000	1,275503776	1,189835612

M	P_o/P
0,56	1,06272
0,51735	T_o/T
0,58	1,06728

$$\frac{T_o/T - 1{,}06272}{1{,}06728 - 1{,}06272} = \frac{0{,}51735 - 0{,}56}{0{,}58 - 0{,}56}$$

$$\frac{T_{o_2}}{T_2} = 1{,}0666758$$

$T_{o_2} = 518{,}69\,k$ (518,688)

Calculadora Online

Choque Normal $M = 2$

$M_2 = 0,57735026$ (0,57735)

$\frac{P_2}{P_1} = 4,5$ (4,5)

$\frac{T_2}{T_1} = 1,6875$ (1,6875)

$\rightsquigarrow T_2 = 486,27$

$\frac{P_{02}}{P_{01}} = 0,72087386$

Calculadora Online

$T_2 = 486,27$

$\frac{P_{02}}{T_{02}} = 0,12087386$

$T_{02} = ?$ Escoamento isentrópico

$M_2 = 0,57735026$

$\frac{T_2}{T_{02}} = 0,9375$

$\Rightarrow T_{02} = \frac{486,27}{0,9375}$

$T_{02} = 518,688$ (518,688)

Calculadora Online

$T_2 = 486,27$

$\frac{p_{01}}{p_{02}} = 0,12087386$

p_{01} ? Escoamento isentrópico

$M_1 = 2 \rightsquigarrow \frac{p}{p_0} = 0,12780452$

$p_{01} = \frac{101,325}{0,12780452} \rightsquigarrow p_{01} = 792,8123\ kPa$

$p_{02} = 571,5516\ kPa$ (571,5175)

Formulário e Tabelas disponíveis em

www.cienciastermicas.com

CIÊNCIAS TÉRMICAS .com