Сверхзвуковой поток (режим сопла Лаваля со скачком) по эксперименту

$$U1 := \begin{pmatrix} 0.9305 \\ 0.9187 \\ 0.4903 \\ 0.4384 \\ 0.3851 \\ 0.3948 \\ 0.3773 \\ 0.5143 \\ 0.7285 \\ 0.7542 \\ 0.7676 \\ 0.7805 \end{pmatrix} \qquad p := 98000\cdot\left(\frac{U1}{0.8} - 1\right) + 100000$$

p =

	0
0	$1.15986\cdot10^{5}$
1	$1.14541\cdot10^{5}$
2	62061.75
3	55704
4	49174.75
5	50363
6	48219.25
7	65001.75
8	91241.25
9	94389.5
10	96031
11	97611.25

$$\varepsilon := \frac{p}{p_0}$$

ε =

	0
0	1
1	0.98754
2	0.53508
3	0.48026
4	0.42397
5	0.43422
6	0.41573
7	0.56043
8	0.78666
9	0.8138
10	0.82795
11	0.84158

$$x := \begin{pmatrix} 0 \\ 0.06 \\ 0.164 \\ 0.184 \\ 0.204 \\ 0.224 \\ 0.244 \\ 0.284 \\ 0.604 \\ 0.764 \\ 0.924 \\ 1 \end{pmatrix}$$

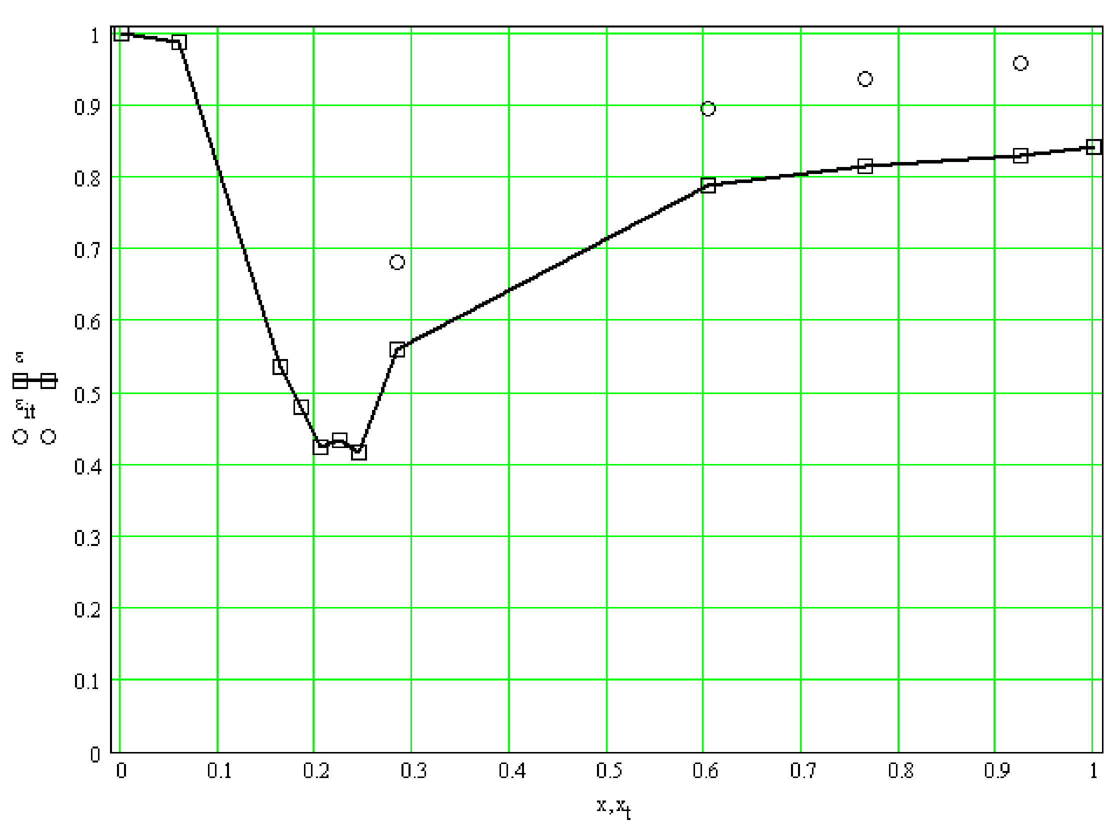
$\varepsilon_c := 0.98754$ $\varepsilon_1 := 0.53508$ $\varepsilon_2 := 0.48026$

$\varepsilon_3 := 0.42397$ $\varepsilon_4 := 0.43422$ $\varepsilon_5 := 0.41573$

$\varepsilon_6 := 0.56043$ $\varepsilon_7 := 0.78666$ $\varepsilon_8 := 0.8138$

$\varepsilon_9 := 0.82795$

$$\varepsilon_{it} := \begin{pmatrix} 0.68002 \\ 0.89503 \\ 0.93603 \\ 0.95703 \end{pmatrix} \qquad x_t := \begin{pmatrix} 0.284 \\ 0.604 \\ 0.764 \\ 0.924 \end{pmatrix}$$



По эксперименту

Скачок давления расположен между дренажами номер 5 и 6

Найдём скорость перед скачком λ1: $\varepsilon_{перед\_скачком} := \frac{0.41573 + 0.56043}{2}$ $\varepsilon_{перед\_скачком} = 0.48808$

По таблицам, при ε = 0.48808 λ1 = 1,06 Значит, скорость за скачком $\lambda2 := \frac{1}{1.06}$ $\lambda2 = 0.9434$

По газодинамическим таблицам определяем q2 и ε' 2 за скачком q2 = 0.99567 ε' 2 = 0.57259

$d_{ск} := \frac{21.369 + 22.096}{2}$ $d_{ск} = 21.7325$ $q_6 := \frac{0.98265\cdot d_{ск}^{\,2}}{(22.096)^2}$ $q_6 = 0.95058$ $q_7 := \frac{0.98265\cdot d_{ск}^{\,2}}{(27.682)^2}$ $q_7 = 0.60565$

$q_8 := \frac{0.98265\cdot d_{ск}^{\,2}}{(30.476)^2}$ $q_8 = 0.49969$ $q_9 := \frac{0.98265\cdot d_{ск}^{\,2}}{(33.268)^2}$ $q_9 = 0.41934$

По газодинамическим таблицам определяем ε'_{it}

$\varepsilon_0 = \frac{P_{02}}{P_{01}} = \frac{q(\lambda_1)}{q(\lambda_2)}$ $\varepsilon_0 := \frac{0.9957}{0.99567}$ $\varepsilon_0 = 1.00003$

Определяем ε_{it} $\varepsilon_{it6} := 0.68\cdot\varepsilon_0$ $\varepsilon_{it6} = 0.68002$ $\varepsilon_{it7} := 0.895\cdot\varepsilon_0$ $\varepsilon_{it7} = 0.89503$

$\varepsilon_{it8} := 0.936\cdot\varepsilon_0$ $\varepsilon_{it8} = 0.93603$ $\varepsilon_{it9} := 0.957\cdot\varepsilon_0$ $\varepsilon_{it9} = 0.95703$

Расчётный режим течения в сопле Лаваля :

$$d := \begin{pmatrix} 43.5 \\ 20 \\ 20.35 \\ 20.69 \\ 21.048 \\ 21.396 \\ 22.096 \\ 27.682 \\ 30.476 \\ 33.268 \end{pmatrix} \qquad q := \frac{400}{d^2}$$

q =

	0
0	0.21139
1	1
2	0.9659
3	0.93441
4	0.9029
5	0.87377
6	0.81928
7	0.52199
8	0.43067
9	0.36142

κ := 1.4

Первое приближение:

λc := 0.1 λ1 := 2 λ2 := 2 λ3 := 2 λ4 := 2

λ5 := 2 λ6 := 2 λ7 := 2 λ8 := 2 λ9 := 2

Given

$$q_0 = \left(\frac{\kappa+1}{2}\right)^{\frac{1}{\kappa-1}}\cdot\left(1 - \frac{\kappa-1}{\kappa+1}\cdot\lambda c^2\right)^{\frac{1}{\kappa-1}}\cdot\lambda c \qquad q_2 = \left(\frac{\kappa+1}{2}\right)^{\frac{1}{\kappa-1}}\cdot\left(1 - \frac{\kappa-1}{\kappa+1}\cdot\lambda 2^2\right)^{\frac{1}{\kappa-1}}\cdot\lambda 2$$

$$q_1 = \left(\frac{\kappa+1}{2}\right)^{\frac{1}{\kappa-1}}\cdot\left(1 - \frac{\kappa-1}{\kappa+1}\cdot\lambda 1^2\right)^{\frac{1}{\kappa-1}}\cdot\lambda 1 \qquad q_3 = \left(\frac{\kappa+1}{2}\right)^{\frac{1}{\kappa-1}}\cdot\left(1 - \frac{\kappa-1}{\kappa+1}\cdot\lambda 3^2\right)^{\frac{1}{\kappa-1}}\cdot\lambda 3$$

$$q_4 = \left(\frac{\kappa+1}{2}\right)^{\frac{1}{\kappa-1}}\cdot\left(1 - \frac{\kappa-1}{\kappa+1}\cdot\lambda 4^2\right)^{\frac{1}{\kappa-1}}\cdot\lambda 4 \qquad q_5 = \left(\frac{\kappa+1}{2}\right)^{\frac{1}{\kappa-1}}\cdot\left(1 - \frac{\kappa-1}{\kappa+1}\cdot\lambda 5^2\right)^{\frac{1}{\kappa-1}}\cdot\lambda 5$$

$$q_6 = \left(\frac{\kappa+1}{2}\right)^{\frac{1}{\kappa-1}}\cdot\left(1 - \frac{\kappa-1}{\kappa+1}\cdot\lambda 6^2\right)^{\frac{1}{\kappa-1}}\cdot\lambda 6 \qquad q_7 = \left(\frac{\kappa+1}{2}\right)^{\frac{1}{\kappa-1}}\cdot\left(1 - \frac{\kappa-1}{\kappa+1}\cdot\lambda 7^2\right)^{\frac{1}{\kappa-1}}\cdot\lambda 7$$

$$q_8 = \left(\frac{\kappa+1}{2}\right)^{\frac{1}{\kappa-1}}\cdot\left(1 - \frac{\kappa-1}{\kappa+1}\cdot\lambda 8^2\right)^{\frac{1}{\kappa-1}}\cdot\lambda 8 \qquad q_9 = \left(\frac{\kappa+1}{2}\right)^{\frac{1}{\kappa-1}}\cdot\left(1 - \frac{\kappa-1}{\kappa+1}\cdot\lambda 9^2\right)^{\frac{1}{\kappa-1}}\cdot\lambda 9$$

Find(λc, λ1, λ2, λ3, λ4, λ5, λ6, λ7, λ8, λ9) =

	0
0	0.13503
1	1.00032
2	1.17022
3	1.23753
4	1.29072
5	1.33325
6	1.40276
7	1.69705
8	1.77905
9	1.84217

$$\lambda := \begin{pmatrix} 0.13503 \\ 1.00032 \\ 1.17022 \\ 1.23753 \\ 1.29072 \\ 1.33325 \\ 1.40276 \\ 1.69705 \\ 1.77905 \\ 1.84217 \end{pmatrix} \qquad x := \begin{pmatrix} 0.06 \\ 0.164 \\ 0.184 \\ 0.204 \\ 0.224 \\ 0.244 \\ 0.284 \\ 0.604 \\ 0.764 \\ 0.924 \end{pmatrix}$$

i := 0 .. 9

λc := 0.1 λ1 := 0.1 λ2 := 0.1 λ3 := 0.1 λ4 := 0.1 λ5 := 0.1 λ6 := 0.1 λ7 := 0.1 λ8 := 0.1 λ9 := 0.1

Given

$$q_0 = \left(\frac{\kappa+1}{2}\right)^{\frac{1}{\kappa-1}}\cdot\left(1 - \frac{\kappa-1}{\kappa+1}\cdot\lambda c^2\right)^{\frac{1}{\kappa-1}}\cdot\lambda c \qquad q_2 = \left(\frac{\kappa+1}{2}\right)^{\frac{1}{\kappa-1}}\cdot\left(1 - \frac{\kappa-1}{\kappa+1}\cdot\lambda 2^2\right)^{\frac{1}{\kappa-1}}\cdot\lambda 2$$

$$q_1 = \left(\frac{\kappa+1}{2}\right)^{\frac{1}{\kappa-1}}\cdot\left(1 - \frac{\kappa-1}{\kappa+1}\cdot\lambda 1^2\right)^{\frac{1}{\kappa-1}}\cdot\lambda 1 \qquad q_3 = \left(\frac{\kappa+1}{2}\right)^{\frac{1}{\kappa-1}}\cdot\left(1 - \frac{\kappa-1}{\kappa+1}\cdot\lambda 3^2\right)^{\frac{1}{\kappa-1}}\cdot\lambda 3$$

$$q_4 = \left(\frac{\kappa+1}{2}\right)^{\frac{1}{\kappa-1}}\cdot\left(1 - \frac{\kappa-1}{\kappa+1}\cdot\lambda 4^2\right)^{\frac{1}{\kappa-1}}\cdot\lambda 4 \qquad q_5 = \left(\frac{\kappa+1}{2}\right)^{\frac{1}{\kappa-1}}\cdot\left(1 - \frac{\kappa-1}{\kappa+1}\cdot\lambda 5^2\right)^{\frac{1}{\kappa-1}}\cdot\lambda 5$$

$$q_6 = \left(\frac{\kappa+1}{2}\right)^{\frac{1}{\kappa-1}}\cdot\left(1 - \frac{\kappa-1}{\kappa+1}\cdot\lambda 6^2\right)^{\frac{1}{\kappa-1}}\cdot\lambda 6 \qquad q_7 = \left(\frac{\kappa+1}{2}\right)^{\frac{1}{\kappa-1}}\cdot\left(1 - \frac{\kappa-1}{\kappa+1}\cdot\lambda 7^2\right)^{\frac{1}{\kappa-1}}\cdot\lambda 7$$

$$q_8 = \left(\frac{\kappa+1}{2}\right)^{\frac{1}{\kappa-1}}\cdot\left(1 - \frac{\kappa-1}{\kappa+1}\cdot\lambda 8^2\right)^{\frac{1}{\kappa-1}}\cdot\lambda 8 \qquad q_9 = \left(\frac{\kappa+1}{2}\right)^{\frac{1}{\kappa-1}}\cdot\left(1 - \frac{\kappa-1}{\kappa+1}\cdot\lambda 9^2\right)^{\frac{1}{\kappa-1}}\cdot\lambda 9$$

Find(λc, λ1, λ2, λ3, λ4, λ5, λ6, λ7, λ8, λ9) =

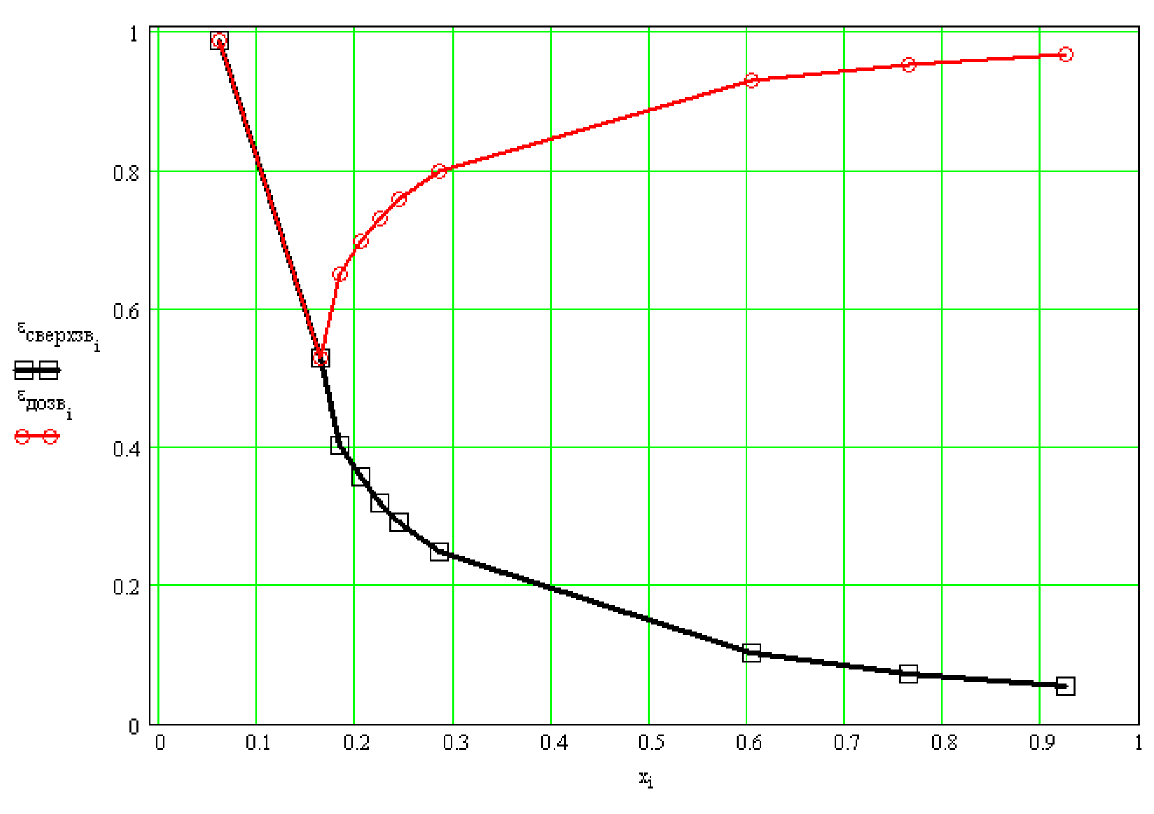
	0
0	0.13503
1	1.0006
2	0.83173
3	0.76635
4	0.71521
5	0.6747
6	0.60929
7	0.34824
8	0.2823
9	0.23445

$$\lambda_{дозвук} := \begin{pmatrix} 0.13503 \\ 1.0006 \\ 0.83173 \\ 0.76635 \\ 0.71521 \\ 0.6747 \\ 0.60929 \\ 0.34824 \\ 0.2823 \\ 0.23445 \end{pmatrix}$$

$$M_{дозвук_i} := \sqrt{\frac{2\cdot\left(\lambda_{дозвук_i}\right)^2}{(\kappa+1) - (\kappa-1)\cdot\left(\lambda_{дозвук_i}\right)^2}} \qquad M_i := \sqrt{\frac{2\cdot(\lambda_i)^2}{(\kappa+1) - (\kappa-1)\cdot(\lambda_i)^2}}$$

$$\varepsilon_{сверхзв_i} := \frac{1}{\left[\frac{\kappa-1}{2}\cdot\left(M_i\right)^2 + 1\right]^{\frac{\kappa}{\kappa-1}}} \qquad \varepsilon_{дозв_i} := \frac{1}{\left[\frac{\kappa-1}{2}\cdot\left(M_{дозвук_i}\right)^2 + 1\right]^{\frac{\kappa}{\kappa-1}}}$$

$\varepsilon_{дозв_i} =$	$\varepsilon_{сверхзв_i} =$
0.9894	0.9894
0.52784	0.52805
0.65132	0.40383
0.6973	0.35649
0.73207	0.32033
0.75869	0.29238
0.79968	0.24882
0.93103	0.1014
0.95428	0.07251
0.9683	0.05403



Экспериментальный режим сопла Вентури

$$U2 := \begin{pmatrix} 0.7843 \\ 0.7834 \\ 0.7662 \\ 0.7667 \\ 0.7674 \\ 0.7688 \\ 0.7692 \\ 0.7704 \\ 0.7773 \\ 0.7786 \\ 0.7794 \\ 0.7806 \end{pmatrix} \qquad p := 98000\cdot\left(\frac{U2}{0.8} - 1\right) + 100000$$

Число маха для ε:

p =

	0
0	98076.75
1	97966.5
2	95859.5
3	95920.75
4	96006.5
5	96178
6	96227
7	96374
8	97219.25
9	97378.5
10	97476.5
11	97623.5

i := 1 .. 10

$$\varepsilon_i := \frac{p_i}{p_0}$$

$\varepsilon_i =$

0.99888
0.97739
0.97802
0.97889
0.98064
0.98114
0.98264
0.99126
0.99288
0.99388

$$d := \begin{pmatrix} 500 \\ 43.5 \\ 20 \\ 20.35 \\ 20.69 \\ 21.048 \\ 21.396 \\ 22.096 \\ 27.682 \\ 30.476 \\ 33.268 \end{pmatrix}$$

$$M_i := \sqrt{\frac{2\cdot\left[\left(\frac{1}{\varepsilon_i}\right)^{\frac{\kappa-1}{\kappa}} - 1\right]}{\kappa - 1}}$$

$M_i =$

	0
0	0.04009
1	0.18104
2	0.17848
3	0.17485
4	0.16735
5	0.16515
6	0.15837
7	0.11208
8	0.10108
9	0.09369

$$\lambda_i := \sqrt{\frac{(\kappa+1)\cdot\left(M_i\right)^2}{2 + (\kappa-1)\cdot\left(M_i\right)^2}}$$

$$q_i := \left(\frac{\kappa+1}{2}\right)^{\frac{1}{\kappa-1}}\cdot\left[1 - \frac{\kappa-1}{\kappa+1}\cdot(\lambda_i)^2\right]^{\frac{1}{\kappa-1}}\cdot\lambda_i$$

$$d_{\phi_i} := d_i\cdot\sqrt{q_i} \qquad q_{Вентури_i} := \frac{q_i\cdot\left(d_{\phi_i}\right)^2}{\left(d_i\right)^2}$$

$q_i =$	$d_{\phi_i} =$	$q_{Вентури_i} =$	$\lambda_i =$
0.06921	11.4435	0.00479	0.04391
0.30676	11.07713	0.0941	0.19767
0.30259	11.19424	0.09156	0.1949
0.29666	11.26908	0.08801	0.19095
0.28438	11.22426	0.08087	0.18281
0.28076	11.33705	0.07883	0.18042
0.26959	11.47278	0.07268	0.17306
0.19221	12.1364	0.03695	0.12262
0.1736	12.698	0.03014	0.11062
0.16105	13.35062	0.02594	0.10254

Находим λ при режиме Вентури Первое приближение:

λc := 0.1 λ1 := 0.1 λ2 := 0.1 λ3 := 0.1 λ4 := 0.1

λ5 := 0.1 λ6 := 0.1 λ7 := 0.1 λ8 := 0.1 λ9 := 0.1

Given

$$q_{Вентури_1} = \left(\frac{\kappa+1}{2}\right)^{\frac{1}{\kappa-1}}\cdot\left(1 - \frac{\kappa-1}{\kappa+1}\cdot\lambda c^2\right)^{\frac{1}{\kappa-1}}\cdot\lambda c \qquad q_{Вентури_3} = \left(\frac{\kappa+1}{2}\right)^{\frac{1}{\kappa-1}}\cdot\left(1 - \frac{\kappa-1}{\kappa+1}\cdot\lambda 2^2\right)^{\frac{1}{\kappa-1}}\cdot\lambda 2$$

$$q_{Вентури_2} = \left(\frac{\kappa+1}{2}\right)^{\frac{1}{\kappa-1}}\cdot\left(1 - \frac{\kappa-1}{\kappa+1}\cdot\lambda 1^2\right)^{\frac{1}{\kappa-1}}\cdot\lambda 1 \qquad q_{Вентури_4} = \left(\frac{\kappa+1}{2}\right)^{\frac{1}{\kappa-1}}\cdot\left(1 - \frac{\kappa-1}{\kappa+1}\cdot\lambda 3^2\right)^{\frac{1}{\kappa-1}}\cdot\lambda 3$$

$$q_{Вентури_5} = \left(\frac{\kappa+1}{2}\right)^{\frac{1}{\kappa-1}}\cdot\left(1 - \frac{\kappa-1}{\kappa+1}\cdot\lambda 4^2\right)^{\frac{1}{\kappa-1}}\cdot\lambda 4 \qquad q_{Вентури_6} = \left(\frac{\kappa+1}{2}\right)^{\frac{1}{\kappa-1}}\cdot\left(1 - \frac{\kappa-1}{\kappa+1}\cdot\lambda 5^2\right)^{\frac{1}{\kappa-1}}\cdot\lambda 5$$

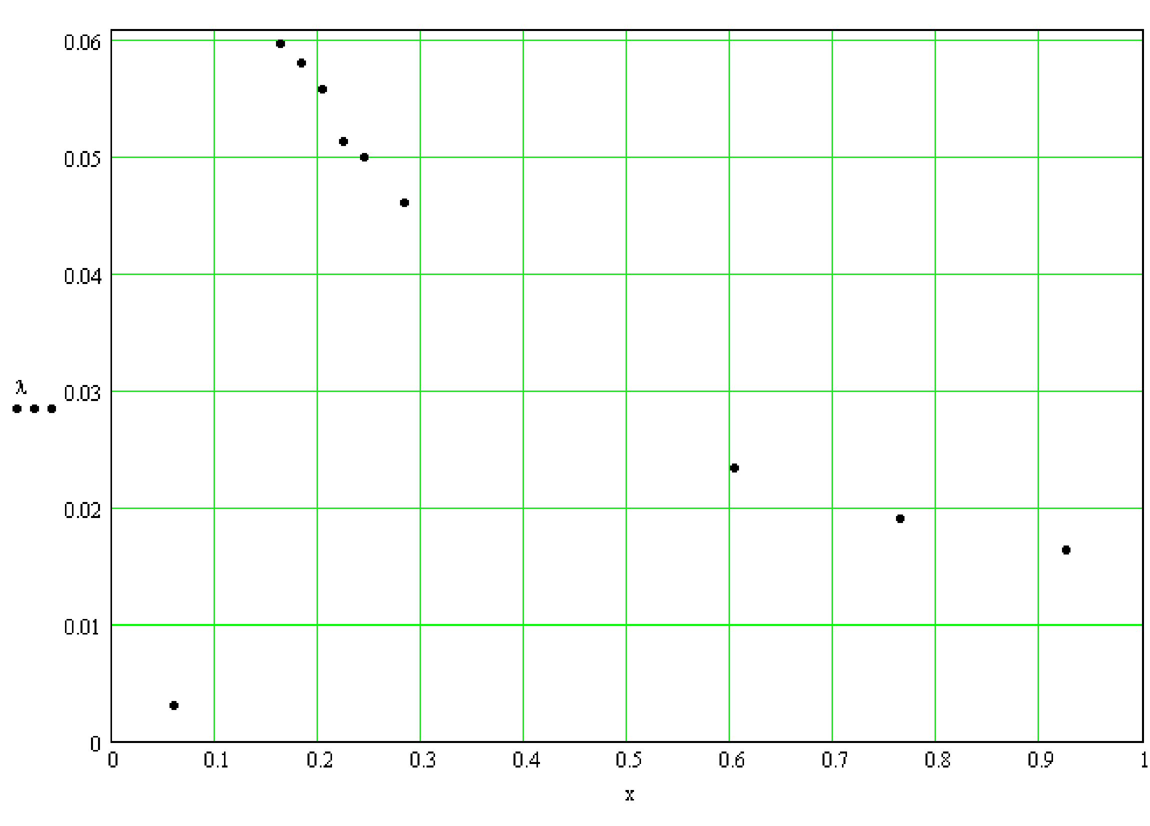
$$q_{Вентури_7} = \left(\frac{\kappa+1}{2}\right)^{\frac{1}{\kappa-1}}\cdot\left(1 - \frac{\kappa-1}{\kappa+1}\cdot\lambda 6^2\right)^{\frac{1}{\kappa-1}}\cdot\lambda 6 \qquad q_{Вентури_8} = \left(\frac{\kappa+1}{2}\right)^{\frac{1}{\kappa-1}}\cdot\left(1 - \frac{\kappa-1}{\kappa+1}\cdot\lambda 7^2\right)^{\frac{1}{\kappa-1}}\cdot\lambda 7$$

$$q_{Вентури_9} = \left(\frac{\kappa+1}{2}\right)^{\frac{1}{\kappa-1}}\cdot\left(1 - \frac{\kappa-1}{\kappa+1}\cdot\lambda 8^2\right)^{\frac{1}{\kappa-1}}\cdot\lambda 8 \qquad q_{Вентури_{10}} = \left(\frac{\kappa+1}{2}\right)^{\frac{1}{\kappa-1}}\cdot\left(1 - \frac{\kappa-1}{\kappa+1}\cdot\lambda 9^2\right)^{\frac{1}{\kappa-1}}\cdot\lambda 9$$

Find(λc, λ1, λ2, λ3, λ4, λ5, λ6, λ7, λ8, λ9) =

	0
0	0.00304
1	0.05974
2	0.05813
3	0.05586
4	0.05132
5	0.05002
6	0.04612
7	0.02343
8	0.01911
9	0.01644

$$\lambda := \begin{pmatrix} 0.00304 \\ 0.05974 \\ 0.05813 \\ 0.05586 \\ 0.05132 \\ 0.05002 \\ 0.04612 \\ 0.02343 \\ 0.01911 \\ 0.01644 \end{pmatrix}$$



i := 0 .. 9

$$M_i := \sqrt{\frac{2\cdot(\lambda_i)^2}{(\kappa+1) - (\kappa-1)\cdot(\lambda_i)^2}} \qquad \varepsilon_i := \frac{1}{\left[\frac{\kappa-1}{2}\cdot\left(M_i\right)^2 + 1\right]^{\frac{\kappa}{\kappa-1}}} \qquad \varepsilon_{пред\_реж_i} := \varepsilon_{дозв_i}$$

$\varepsilon_i =$

0.99999
0.99792
0.99803
0.99818
0.99846
0.99854
0.99876
0.99968
0.99979
0.99984

Эксперементальная зависимость ε от x при режиме течения сопла Вентури и предельный режим трубы вентури