$$\beta = d / D$$

$$\mathrm{Re} = \frac{uD\rho}{\mu} = \frac{4q_m}{\pi\mu D} = \frac{4q_c\rho_c}{\pi\mu D} = \frac{4q_o\rho}{\pi\mu D}$$

æ

$q_m, \rho, \Delta p, d$ D C

$$\varepsilon = \frac{q_m(1-\beta^4)^{1/2}}{C(\pi/4)d^2(2\Delta p\rho)^{1/2}}$$

ε

Ra

$R_{ш}$

		M L T θ	
C $C_{\sim}$			

D		L	
D_{20}		L	

C_{Re} B n

$$C_{\mathrm{Re}} = B / C_{\sim}$$

$$K_{\mathrm{Re}} = \frac{C}{C_{\sim}} = 1 + C_{\mathrm{Re}} (10^6 / \mathrm{Re})^n$$

$C = C$ K_{Re}.

C B C_{Re}

C K_{Re}

C K_{Re}

C

$$K_{\mathrm{Re}} = 1 + \left(\frac{a}{b} - 1\right) / \left[1 + \frac{\mathrm{Re}_{\sim}^{n}}{b C_{\mathrm{Re}} 10^{6n}}\right]$$

$\mathrm{Re}_{\sim}$ $C = C_{\sim}$

a b

a b

$K_{\mathrm{Re}}^{-n} = a - b$ K_{Re}

K_{Re}^{-n} K_{Re}

K_{Re} K_{Re} n

K_{Re}^{-n}

β

$C_{\sim}$

$K_{ш}$

$K_{ш}$ A_{Re}

$C = C_{\sim}$ $q_{m\sim}$

$$q_{m\sim} = C_{\sim} E K_{ш} K_{п} \varepsilon (\pi d^2 / 4)(2\rho \Delta p)^{1/2}$$

$q_{m\sim}$

$$\mathrm{Re}_{\sim} = \frac{4 q_{m\sim}}{\pi \mu D}$$

K_{Re}

$$\mathrm{Re} = \mathrm{Re}_{\sim} K_{Re}$$

$K_{ш}$

$$q_m = q_{m\sim} K_{Re}$$

$K'_{ш}$

$$q_m = q_{m\sim} K_{Re} K'_{ш} / K_{ш}$$

D

D

D D

$\leq$ D $\leq$ D										
D D D										

	δ_L δ_L									
	β									

$L_{к1}$ L_1	δ_L	$L_{к1}$ L_1	δ_L	$L_{к1}$ L_1	δ_L

D

D

δ_L

D

D D

$a_к, b_к, c_к$

$L_{к2}$

β

β

$$L_{к2} = 0{,}5(a_к + b_к 0{,}7^{c_к})$$

$L_{к2}$

	$L_{к2}$

D

D

$$L_{1р} < L_{к1} \quad L_{2р} < L_{к2}$$

$L_{1р}$ $L_{2р}$

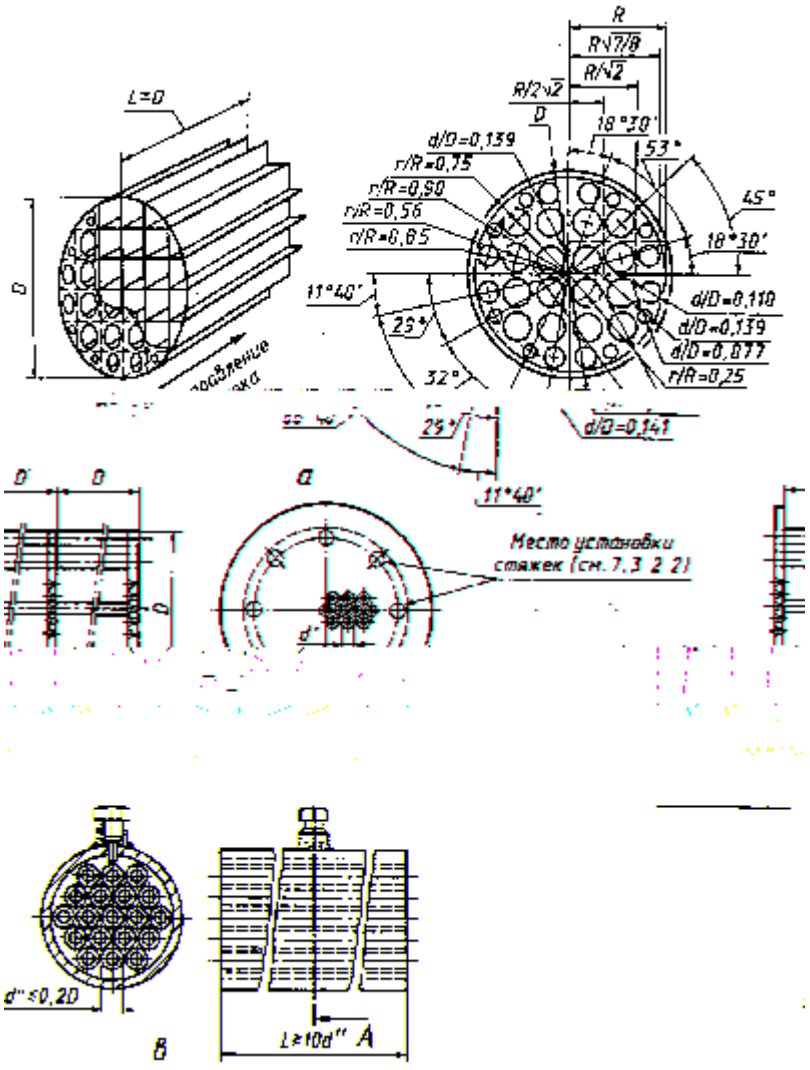
$L_{к1}$ $L_{к2}$

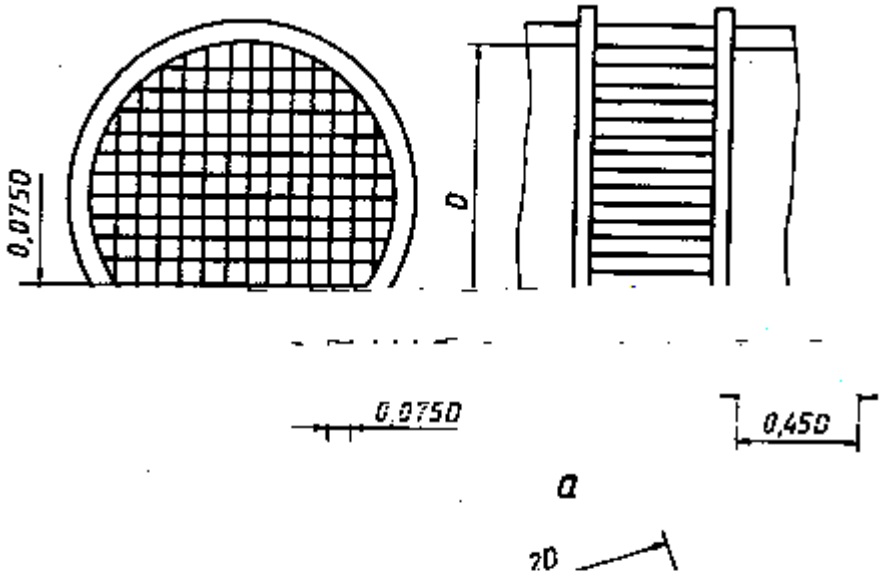
$$L_1 = L_{1р} + L_{2р} - L_{к2}$$

δ_L

L_1

D





D

D

D

D

D

D

D D

D D

D

D D

h

$$h / D \le 0{,}002(l_h / D + 0{,}4) / (0{,}1 + 2{,}3\beta^4)$$

l_h

$$h / D \le 0{,}05$$

δ_h

D

D D

e_x

$$e_x \leq \frac{0{,}0025D}{0{,}1 + 2{,}3\beta^4}$$

$$\frac{0{,}0025D}{0{,}1 + 2{,}3\beta^4} < e_x \leq \frac{0{,}0025D}{0{,}1 + 2{,}3\beta^4}$$

δ_{e_x}

D

D

D

D

$R_{ш} / D \le 10^{-3}$

A D

A

A

A

A

Ra $^{-4}{}_{d}$

D

δ_E

$$\delta_E = \frac{\Delta\varphi_в}{E_у} \cdot \frac{D^2}{E_д^2}\left(a \cdot \frac{D}{E_д} - b\right)$$

$E_у$

$$a = \beta(13{,}5 - 15{,}5\beta)$$

l_1 D

D D

l_2 D

D D $\beta \leq$

D D β

l_1 l_2

l_1

l'_2

l_1 l'_2

β D

$\beta \leq$

β $\leq D \leq$

D

a a

$D \leq a \leq$ D $\beta \leq$

$D \leq a \leq$ D $\beta >$

β a

$\leq a \leq$

$\leq a \leq$

$\leq a \leq$

2

b

D b

$$D \leq b \leq 1{,}01D.$$

$$\frac{b-D}{D} \cdot \frac{c}{D} \cdot 100 \leq \frac{0{,}1}{0{,}1+2{,}3\beta^4}.$$

c c'

D

f a

gh

j

l_h

$$C = C_{\infty} K_{\mathrm{Re}}$$

$$C_{\infty} = 0{,}5959 + 0{,}0312\beta^{2{,}1} - 0{,}1840\beta^{8} + 0{,}090 L_1 \beta^{4}(1-\beta^{4})^{-1} - 0{,}0337 L_2 \beta^{3}$$

$$K_{\mathrm{Re}} = 1 + \frac{0{,}0029\beta^{2{,}5}}{C_{\infty}}\left[\frac{10^{6}}{\mathrm{Re}}\right]^{0{,}75} = 1 + \frac{1{,}426}{1 + \dfrac{C_{\infty}(\mathrm{Re}_{\infty})^{0{,}75}}{64{,}28\beta^{2{,}5}}}$$

$$1{,}426 = a/b - 1 = 1{,}70049/0{,}70091 - 1$$

$$64{,}28 = 0{,}0029(10^{6})^{0{,}75} b = 0{,}0029(10^{6})^{0{,}75} \cdot 0{,}70091$$

$L_1 = l_1 / D$

$L_2 = l_2 / D$

L_1

$$L_1 \geq \frac{0{,}0390}{0{,}0900} (= 0{,}4333).$$

L_1 L_2

$$L_1 = L_2 = 0$$

L_1

L_2

$$L_1 = L_2 = 25{,}4 / D$$

D

C β D

æ

$\Delta p / p$ β

C

β, Re, D $R_ш / D$

$$\delta_{C_0} = \pm 0{,}6 \qquad \beta \le 0{,}6$$

$$\delta_{C_0} = \pm\beta \qquad \beta > 0{,}6$$

ε β

$\Delta p / p$ æ

$$\delta_{\varepsilon_0} = \pm 4(\Delta p / p) \qquad \beta \le 0{,}75$$

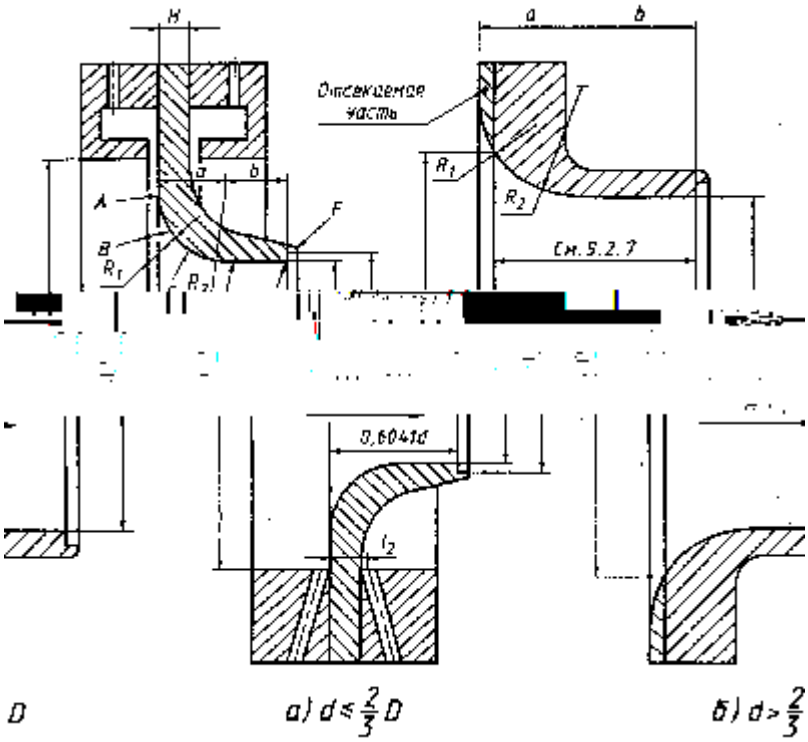
$\Delta\omega$

$$\Delta\omega = \frac{1 - \alpha\beta^2}{1 + \alpha\beta^2}\Delta p$$

D

D

$$\Delta\omega = (1 - \beta^{1{,}9})\Delta p$$



D

а) $d \leq \frac{2}{3} D$

б) $d > \frac{2}{3}$

C B E R_2 d β
d $\beta \geq$

d d d a

$$a = \frac{12 + 39^{0,5}}{60} d = 0,3041d$$

E d b d d

F c d d
c d

f

d $d \leq$ d D

β

d $\leq \beta \leq$

$$\left[0,4041 + \left(\frac{0,75}{\beta} - \frac{0,25}{\beta^2} - 0,5225\right)^{1/2}\right] d \qquad < \beta \leq$$

$Ra \leq 10^{-4} d$

H D

l_2

$l_2 \leq \quad D \quad \beta \leq$

$l_2 \leq \quad D \quad \beta$

$\leq D \leq$

$\leq \beta \leq$

$^4 \leq \mathrm{Re} \leq \quad ^7 \quad \leq \beta <$

$^4 \leq \mathrm{Re} \leq \quad ^7 \quad \leq \beta \leq$

D

$$\frac{R_{\text{ш}}}{D} \cdot 10^4 \leq 10^{\left[1/(10\beta^4)+5\right]/9}$$

$^{-3}$

$R_{\text{ш}}$

C

$$C = C_{\sim} K_{\mathrm{Re}}$$

$$C_{\sim} = 0{,}9900 - 0{,}2262\beta^{4{,}1}$$

$$K_{\mathrm{Re}} = 1 + \frac{10^{-4}(33\beta^{2{,}15} - 17{,}5)\beta^2}{C_{\sim}} \left[\frac{10^6}{\mathrm{Re}}\right]^{1{,}15} = 1 + \frac{0{,}86}{1 + \dfrac{C_{\sim}(\mathrm{Re}_{\sim})^{1{,}15}}{923{,}9\beta^2(33\beta^{2{,}15} - 17{,}5)}}$$

$$0{,}86 = a/b - 1 = 2{,}16346/1{,}16313 - 1$$

$$923{,}9 = 10^{-4}(10^6)^{1{,}15}\, b = 10^{-4}(10^6)^{1{,}15} \cdot 1{,}16313$$

C β

ε

$$\varepsilon = \left[\left(\frac{æ\psi^{2/æ}}{\quad}\right)\left(\frac{1-\beta^4}{\quad}\right)\left(\frac{1-\psi^{(æ-1)/æ}}{\quad}\right)\right]^{1/2}$$

$$\psi = 1 - \Delta p / p$$

$æ$ $\Delta p / p$ β

C β, D, Re $R_{ш} / D$

δ_{C_0} $\beta \le$

δ_{C_0} β β

ε $\beta, \Delta p / p$ $æ$

$$\delta_{\varepsilon_0} = \pm 2\Delta p / p$$

$\Delta\omega$

$\le D \le$

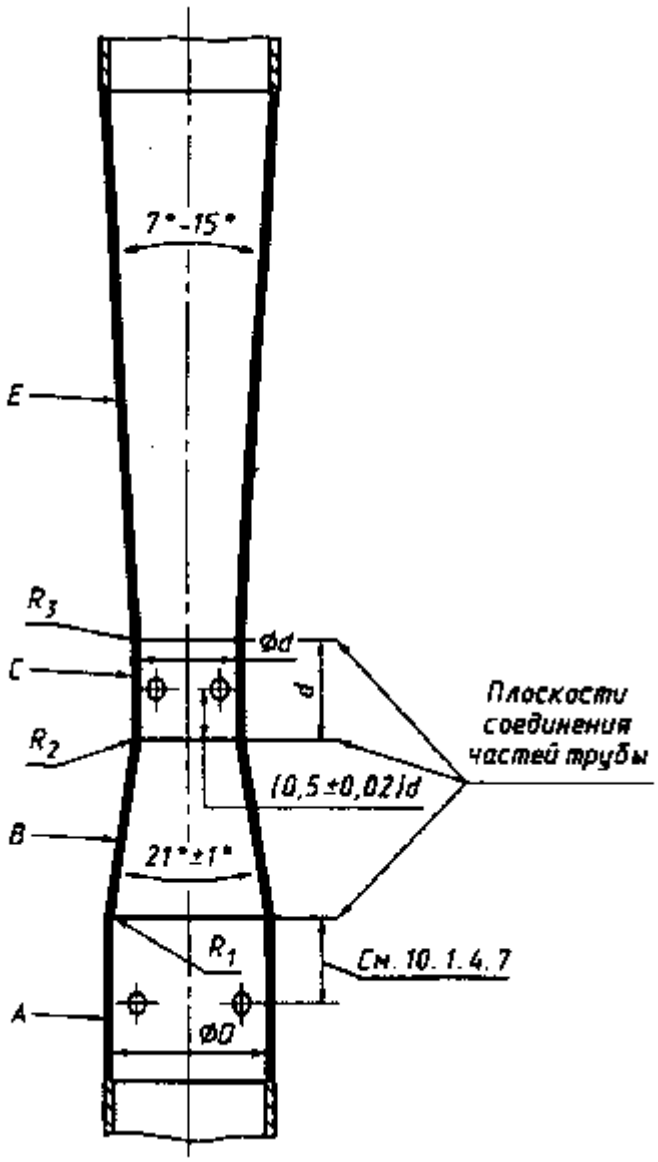
$\le \beta \le$

$\leq D \leq$

$\leq \beta \leq$

$\leq D \leq$

$\leq \beta \leq$



A

B C E

D A

A

B A

D

D

B

B A

B C

B D d

B A R_1

R_1

C d

B C

C E C

d

C R_2

E R_3 R_2 R_3

d

d

d

R_2 R_3

R_3 d

R_3 d d

A D

R_1 D

R_2 d

R_2

d

R_3

d

R_3 d

A D

A ^ Fh B]^ Fh \u

B C

A

Ra

^{-4}D

E

D

d

B A

$0,5D \pm 0,25D$ $\leq D \leq$

$0,5D^{0}_{-0,25D}$ $\leq D \leq$

A B

$0,5D \pm 0,05D$

B C

$0,5d \pm 0,02d$

C

D β

D β 5 6

C

D β 5 6

C

D β 5 6

C

5

C

$4 \leq \mathrm{Re} <$ 5

$4\beta \leq \mathrm{Re} \leq$ $^{5}\beta$

$$C = C_{\sim} K_{\mathrm{Re}}$$

$C_{\sim}$ K_{Re}

$C_{\sim}$

	$C_{\sim}$	K_{Re}
		$1-\frac{0{,}0014\cdot 10^{6}}{C_{\sim}\,\mathrm{Re}} = 0{,}5+\left[0{,}25-\frac{0{,}0014\cdot 10^{6}}{C_{\sim}\,\mathrm{Re}_{\sim}}\right]^{0{,}5}$
		$1{,}009\left[\frac{\beta 10^{6}}{\mathrm{Re}}\right]^{-0{,}013} = 1{,}0091\left[\frac{\beta 10^{6}}{\mathrm{Re}_{\sim}}\right]^{-0{,}0132}$
		$1-\frac{0{,}0013\cdot 10^{6}}{C_{\sim}\,\mathrm{Re}} = 0{,}5+\left[0{,}25-\frac{0{,}0013\cdot 10^{6}}{C_{\sim}\,\mathrm{Re}_{\sim}}\right]^{0{,}5}$

$\Delta p'$

D

D

$\Delta p''$

$\Delta p''$ $\Delta p'$

$$\xi = \frac{\Delta p'' - \Delta p'}{\Delta p}$$ Δp

ξ β

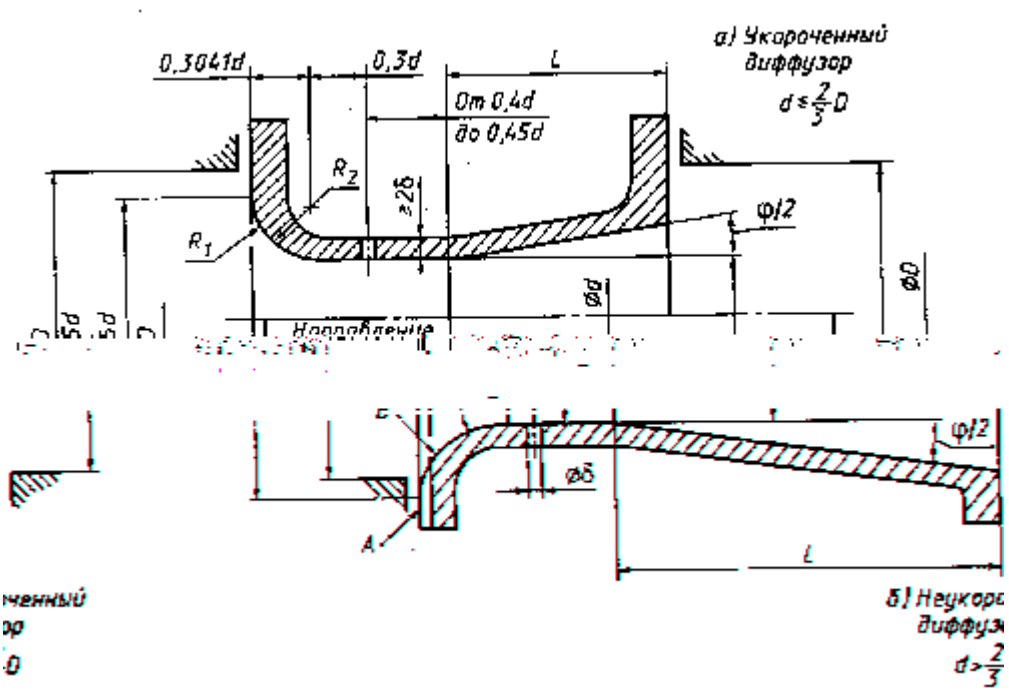
ξ

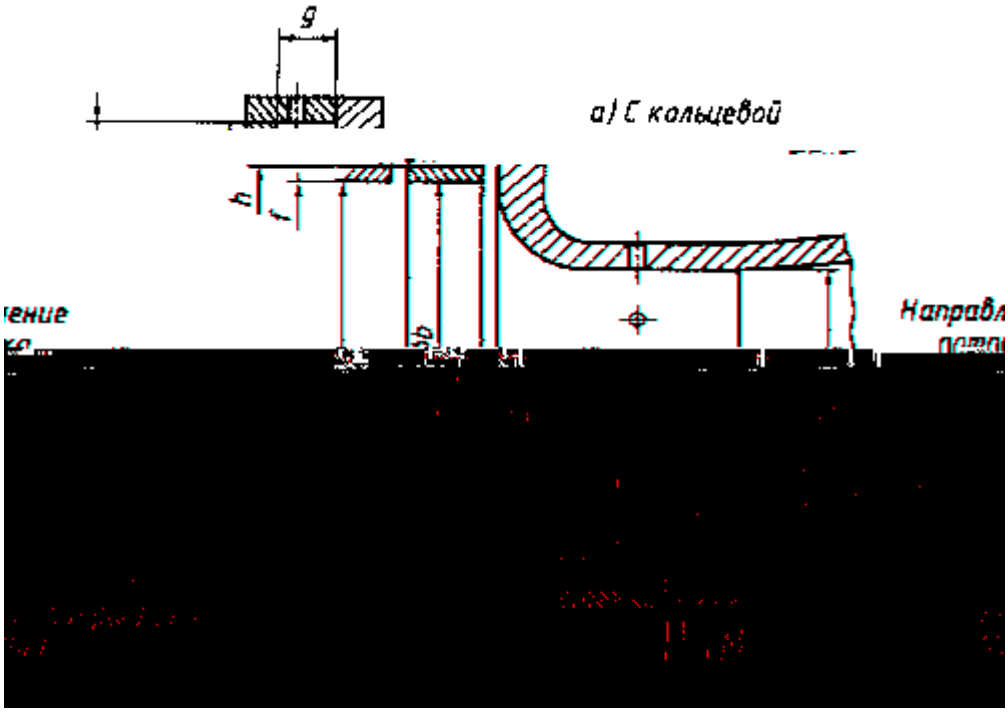
ξ α $R_ш / D$

D

D

$Ra \leq 10^{-4} d$





E E'

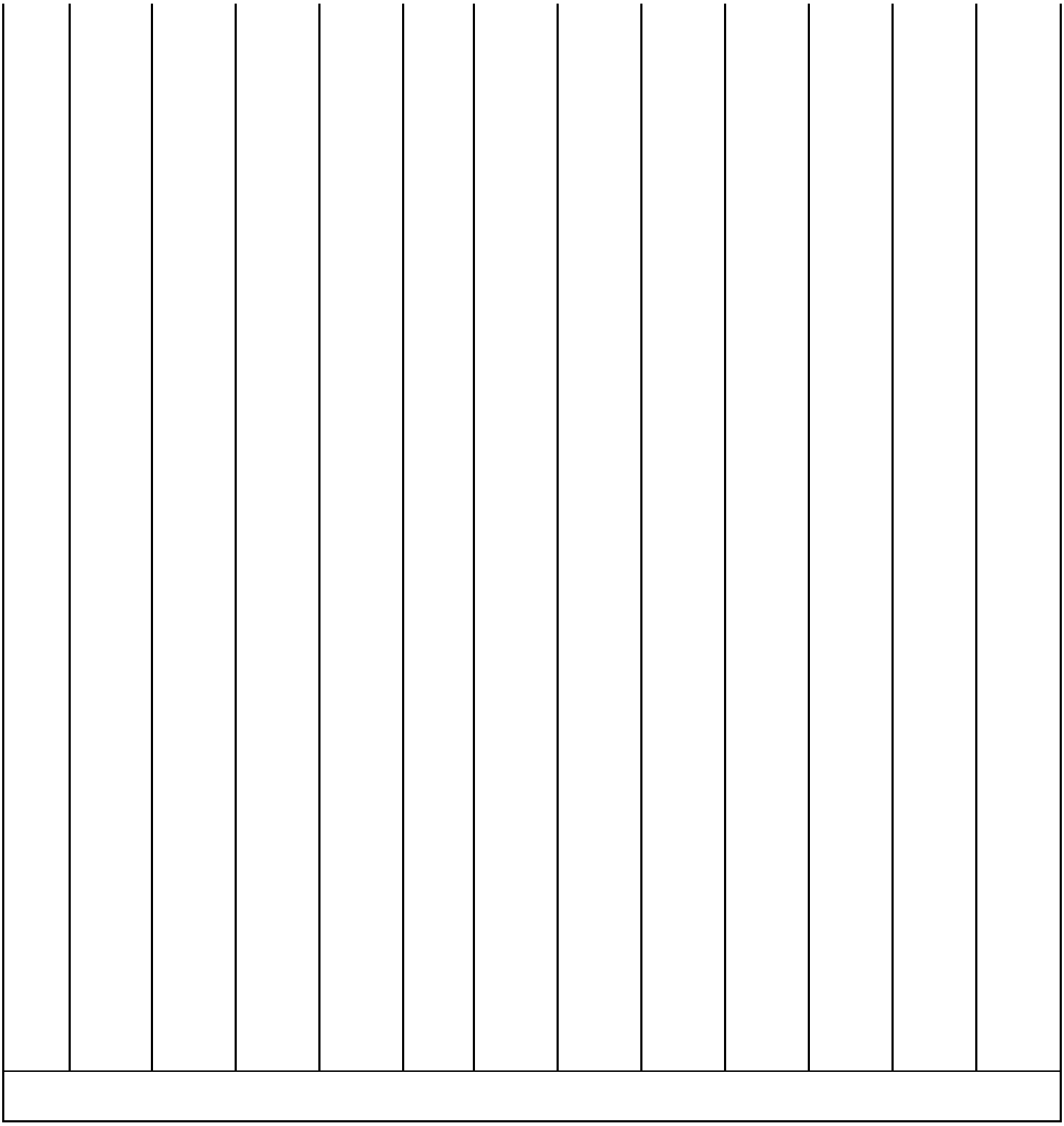
δ d

$\leq D \leq$

$d \geq$

$\leq \beta \leq$

$^{5} \leq \mathrm{Re} \leq$ ^{6}



	3	4	4	4	4	4	5	5	6	7	8	∞

β												
	3	4	4	4	4	4	5	5	6	7	8	∞

C

D

β												
	3	4	4	4	4	4	5	5	6	7	8	∞

β	C / D											
	3	4	4	4	4	4	5	5	6	7	8	∞

C

D

β												
	3	4	4	4	4	4	5	5	6	7	8	∞

C

D

β												
	3	4	4	4	4	4	5	5	6	7	8	∞

C

D

β												
	3	4	4	4	4	4	5	5	6	7	8	∞

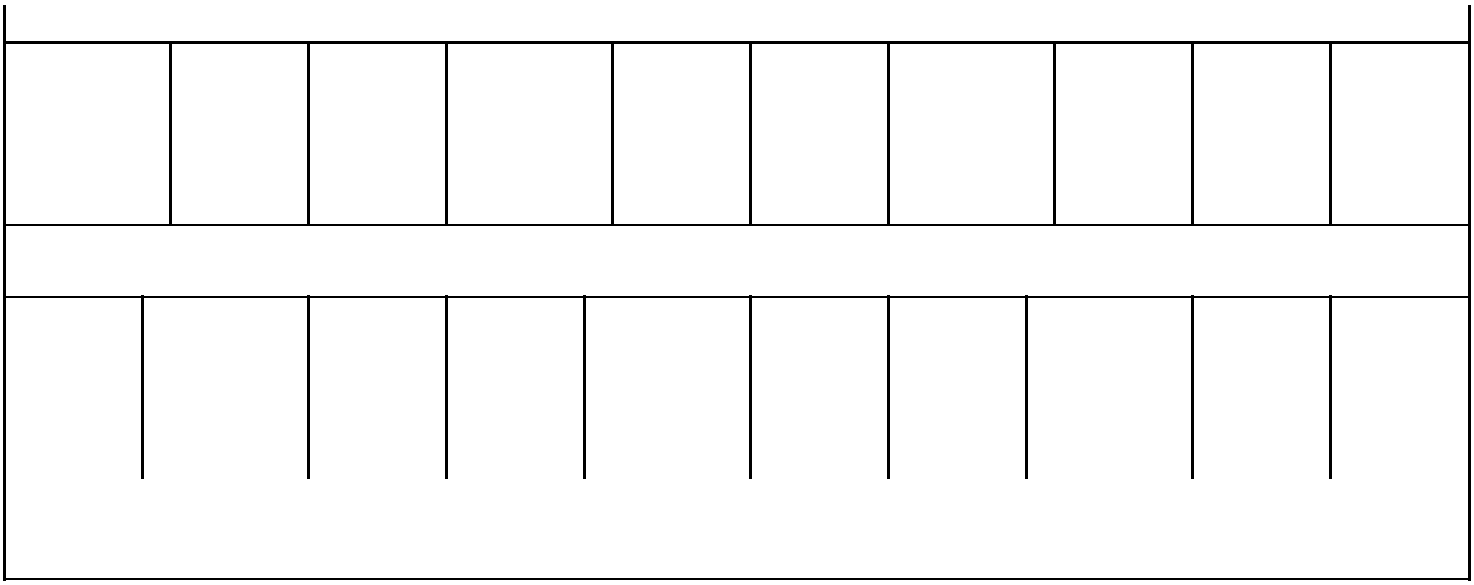
$C_{\sim}$			C		γ				

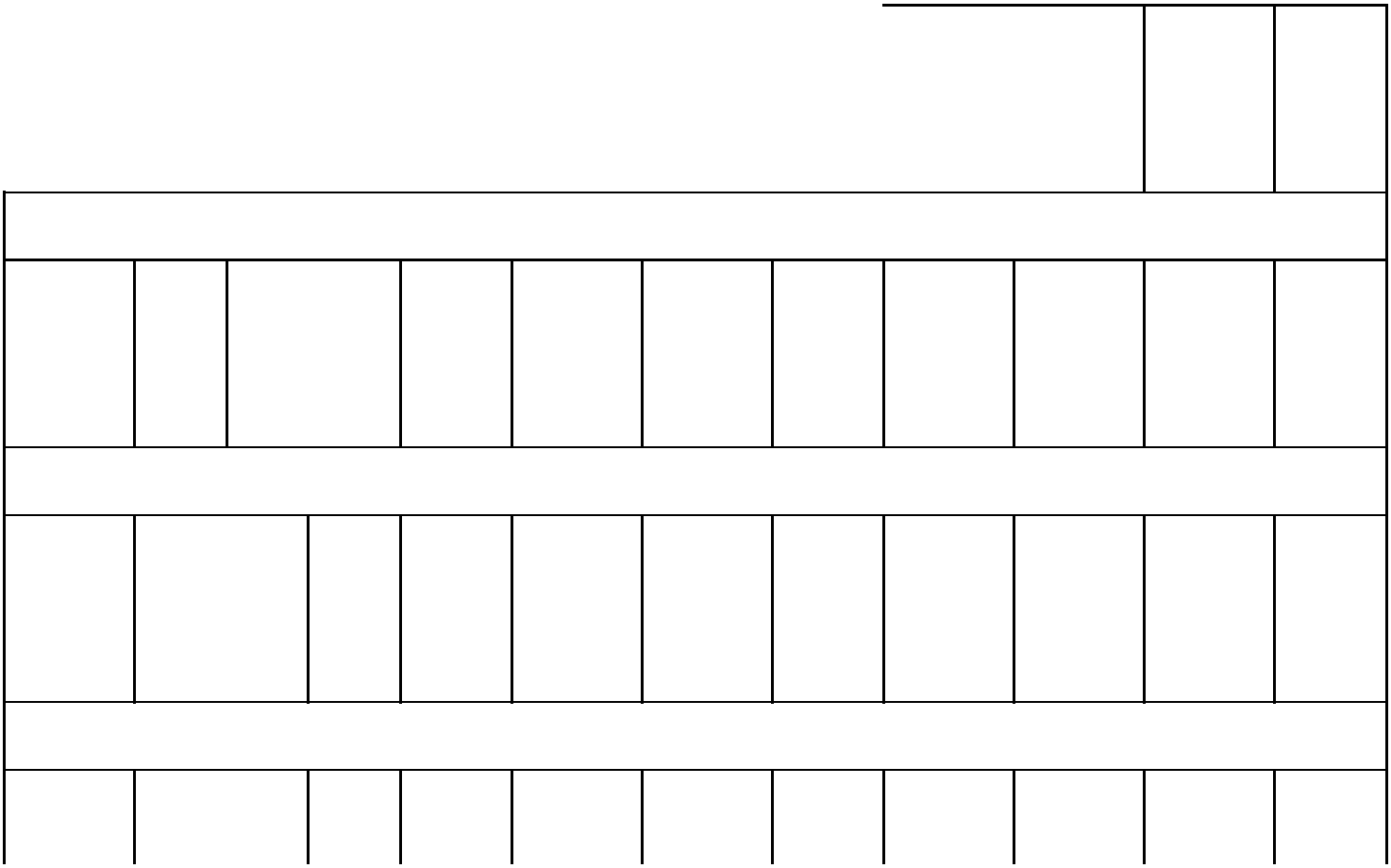
C

β	C	β	C	β	C	β	C	β	C

ε

β	β^4	$1-\Delta p/p$							
æ									
æ									





		$R_{ш}$

$R_{ш}$

$$D_{20} = D / \left[1 + \gamma(t_{\text{и}} - 20)\right] = D / K'_{\text{т}}$$

$t_{\text{и}}$ D

$K'_{\text{т}}$ $t_{\text{и}}$

$$D = D_{20}\left[1 + \gamma(t - 20)\right] = D_{20} K_{\text{т}}$$

$K_{\text{т}}$

	a_e	b_e	c_e

ψ

ψ

D

D

D

D

$$D_2 \leq 1{,}1D_1$$

D_2

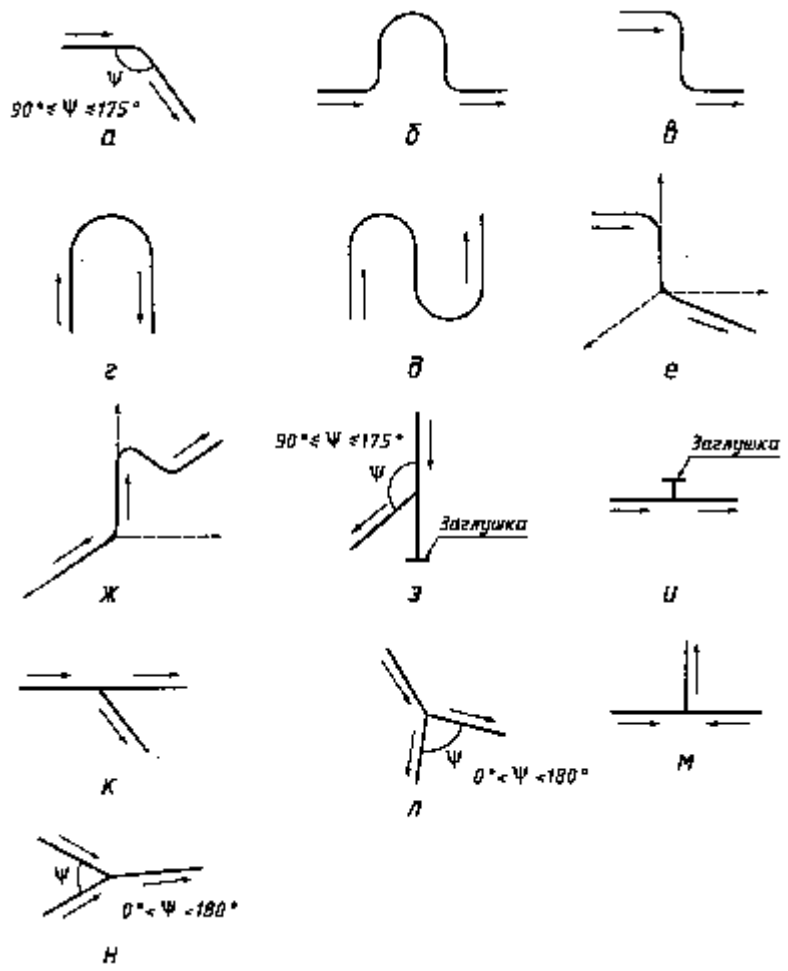
D_1

$$1{,}1D_2 \geq D_1 \geq 0{,}13D_2$$

D_2

D_1

D_1 D_2



D

D

$K_г$

l

$$K_г = D_1 (D_2 / D_1 - 1) / l$$

D_1 D_2 $D_2 > D_1$

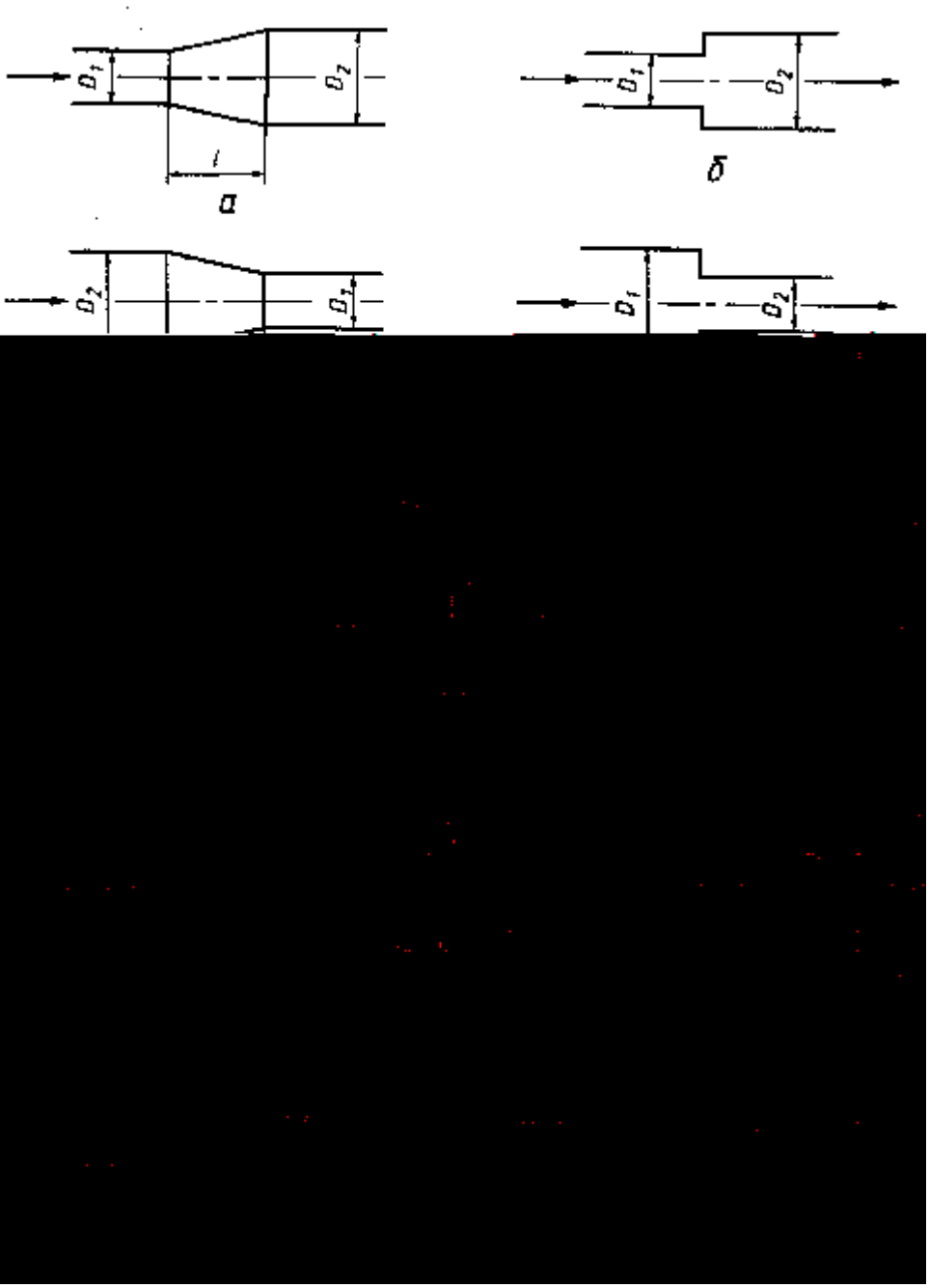
$K_г > 0,7$

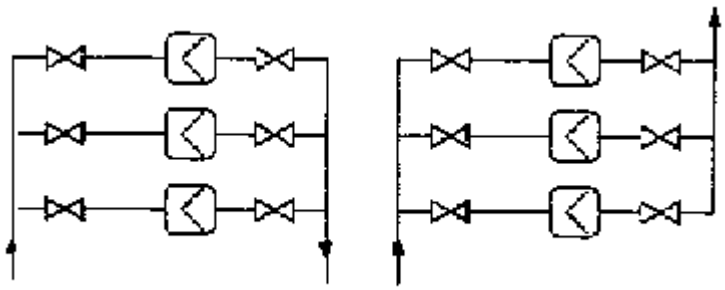
$1,006 \le D_2 / D_1 \le 1,100$

$h = (D_2 - D_1) / 2$

$K_г > 0,7$

$D_2 / D_1 > 1,1$


D1
D2
l
а
D1
D2
б
D2
D1
D1
D2



а *б*

$$D[0{,}5(n+1)]^{0{,}5} \le D_{\text{к}}$$

n

$D_к$

$$D_к > Dn^{0,5}$$

D D

$K_ш$ $K_ш$

$R_ш / D \le 30 \cdot 10^{-4}$

$$K_ш = 1 + \beta^4 r_0 A_{Re}$$

$$A_{Re} = 1 - \frac{(\lg Re - 6)^2}{4}$$ 4 6

$A_{Re} = 1$ $\ge$ 6

$$r_0 = 0{,}045 \lg\left(\frac{R_ш}{D} \cdot 10^4\right) - 0{,}025$$

$r_к / d$

$r_к / d >$

$r_к / d \leq$

$K_п$

$K_п$

$d <$ $d \geq$ $K_п$

$$K_п = 1{,}0547 - 0{,}057e^{-149\bar{r}_к / d}$$

$\bar{r}_к$

$$r_к = 0{,}195 - (0{,}195 - r_н)e^{-(\tau_{пп}/3)\tau}$$

$\tau_{п.п}$

τ

$$0 \leq \tau = \frac{\tau_т}{\tau_{п.п}} \leq 1$$

$\tau_т$

$r_н$

τ

$$\bar{r}_к = 0{,}195 - (0{,}195 - r_н)(1 - e^{-\tau_{пп}/3}) \cdot (3/\tau_{п.п})$$

$\tau_{п.п}$

$$(1 - e^{-\tau_{пп}/3})(3/\tau_{п.п}) = 1$$

$\tau_{п.п}$

$$\bar{r}_к = 0{,}0292 + 0{,}850\tau_н$$

$\delta_к$

$$\delta_к = 0{,}5(K_п - 1) \cdot 100$$

$$\delta_{к} = (K_{п} - 1) \cdot 100$$

	$\delta_{к}$

	−3