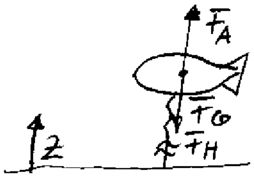
Aufgabe 1

a) Haltekraft: Kräftegleichgewicht am Boden ($z=0$)



$$\sum_i F_{iz} = 0 = F_A - F_G - F_H, \text{ mit } F_G = (m_Z + m_P + m_{Gas})g$$

$$\Rightarrow F_H = F_A(z=0) - (m_Z + m_P + m_{Gas})g$$

$$= \varrho_L(z=0) V_Z g - (m_Z + m_P + \varrho_{Gas}(z=0) V_Z) \cdot g$$

$$= (\varrho_L(z=0) - \varrho_{Gas}(z=0)) V_Z g - (m_Z + m_P) g$$

$$\overset{\text{id. Gas}}{=} \frac{p_a}{T_0}\left(\frac{1}{R_L} - \frac{1}{R_{Gas}}\right) V_Z g - (m_Z + m_P) g$$

$$\Rightarrow F_H(H_2) = 166{,}61\,\text{kN}, \quad F_H(He) = 146{,}22\,\text{kN}$$

b) $z=0$: $m_{ges} a_0 = F_A - F_G$, $\quad m_{ges} = m_Z + m_P + \varrho^*_{Gas} V_Z$

$$\Rightarrow m_{ges}(a_0 + g) = \varrho_L V_Z g$$

$$\Rightarrow \varrho^*_{Gas} = \varrho_L \frac{g}{a_0 + g} - \frac{m_P + m_Z}{V_Z} = 0{,}1546\,\frac{\text{kg}}{\text{m}^3}$$

c) Anfangsbeschleunigung:

$z=0$: $m_{ges} \cdot a = F_A - F_G$

$$\Rightarrow (m_Z + m_P + \varrho_{Gas} V_Z)(a + g) = \varrho_L g V_Z$$

$$\Rightarrow a = \frac{\varrho_L g V_Z}{m_Z + m_P + \varrho_{Gas} V_Z} - g$$

$$\Rightarrow \begin{cases} a_{He} = 9{,}679\,\frac{\text{m}}{\text{s}^2} < a_0 \\ a_{H_2} = 12{,}7467\,\frac{\text{m}}{\text{s}^2} > a_0 \end{cases} ; \quad \text{mit } a_0 = 10\,\frac{\text{m}}{\text{s}^2}$$

d) max. Steighöhe:

$z = z_{max}$: $\sum_i F_{iz} = 0 = F_A(z_{max}) - F_G$

$$\Rightarrow \varrho_L(z_{max}) V_Z g = (m_Z + m_P + \varrho_{Gas} V_Z) g,$$

$$\Rightarrow \frac{p(z_{max})}{R_L T_0} = \frac{(m_Z + m_P)}{V_Z} + \frac{p(z=0)}{R_{Gas} T_0} \quad ; \text{ barometr. Höhenformel: } p(z) = p_0 e^{\left(-\frac{gz}{R_L T_0}\right)}$$

$$\Rightarrow z_{max} = -\frac{R_L T_0}{g} \ln\left\{(m_Z + m_P)\frac{R_L T_0}{p_0 V_Z} + \frac{R_L}{R_{Gas}}\right\} \Rightarrow \begin{cases} z_{max}(He) = 5692{,}3\,\text{m} \\ z_{max}(H_2) = 6911{,}5\,\text{m} \end{cases}$$

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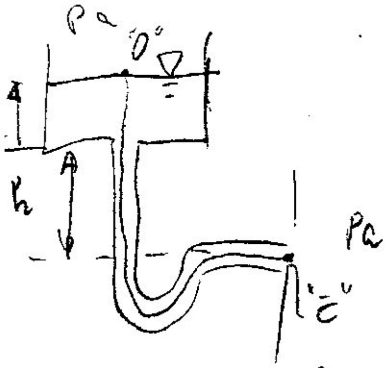
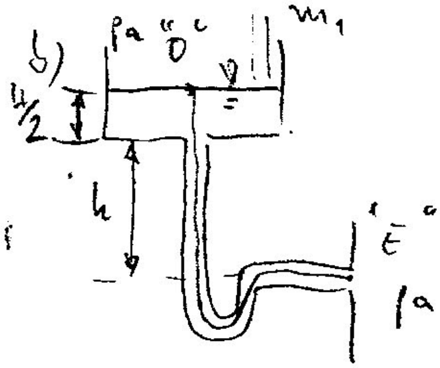
Aufg. 21 a) Bernoulli $0 \to E$



$$A \gg d^2 \Rightarrow \quad p_a + \rho g (h+z) = p_a + \frac{\rho}{2} v_E^2$$

$$\Rightarrow v_E = \sqrt{2g(h+z)}$$

b)



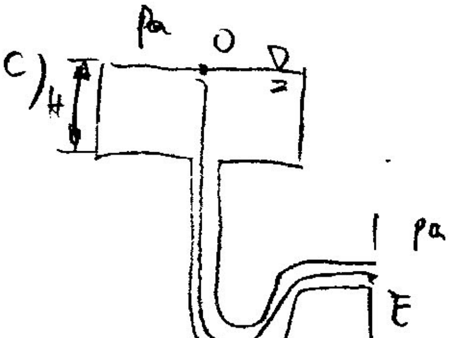
Verlustbeh. Bernoulli $0 \to E$

$$p_a + \rho g \left(h + \frac{H}{2}\right) \geq p_a + \frac{\rho}{2} v_{E1}^2 (1 + \zeta_{Ges})$$

$$\Rightarrow \zeta_{Ges} \leq \frac{2g\left(h + \frac{H}{2}\right)}{v_{E1}^2} - 1$$

mit $v_{E1} = \dfrac{\dot m_1}{\rho \frac{\pi d^2}{4}}$

c)



Verlustbeh. Bernoulli $0 \to E$

$$p_a + \rho g (h + H) = p_a + \frac{\rho}{2} v_{E2}^2 (1 + \zeta_{Ges} + \zeta_V)$$

mit $v_{E2} = \dfrac{4 \dot m_{max}}{\rho \pi d^2}$

$$2g(h+H) = \left(\frac{4 \dot m_{max}}{\rho \pi d^2}\right)^2 \cdot (1 + \zeta_{Ges} + \zeta_V)$$

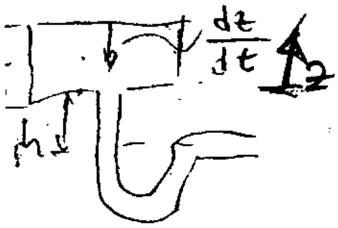
$$\Rightarrow \dot m_{max} = \sqrt{\frac{2g(h+H)}{1 + \zeta_{Ges} + \zeta_V}} \cdot \frac{\rho \pi d^2}{4}$$

$$= \sqrt{\frac{2g(h+H)}{\cancel{1} + \frac{2g(h + H/2)}{v_{E1}^2} - \cancel{1} + \zeta_V}} \; \frac{\rho \pi d^2}{4}$$

$$\dot m_{max} = \sqrt{\frac{(h+H)}{\left(h+\frac{H}{2}\right) + \xi_V \frac{V_{E1}^2}{2g}}} \cdot \frac{\rho\pi d^2}{4} \cdot V_{E1}$$

$$= \sqrt{\frac{(h+H)}{\left(h+\frac{H}{2}\right) + \frac{\xi_V}{2g}\left(\frac{4\dot m_1}{\rho\pi d^2}\right)^2}} \cdot \dot m_1$$

d) Quasistationär : $\int \frac{\partial v}{\partial t}\, ds = 0$



$$\frac{\rho}{2}\left(-\frac{dz}{dt}\right)^2 + \rho g(h+z) = \frac{\rho}{2} v_E^2(t)\,(1+\xi_{Ges})$$

mit Konti : $v_E \frac{\pi d^2}{4} = -\frac{dz}{dt}\cdot A \Rightarrow v_E(t) = -\frac{dz}{dt}\frac{4A}{\pi d^2}$

$$\Rightarrow \left(\frac{dz}{dt}\right)^2 \cdot \left[\left(\frac{4A}{\pi d^2}\right)^2 \cdot (1+\xi_{Ges}) - 1\right] = 2g\,(h+z)$$

Trennung der Variablen :

$$\sqrt{\frac{\left(\frac{4A}{\pi d^2}\right)^2 (1+\xi_{Ges}) - 1}{2g}} \cdot \frac{dz}{\sqrt{h+z}} = dt$$

$$\Rightarrow T = \int_H^0 \underbrace{\sqrt{\frac{\left(\frac{4A}{\pi d^2}\right)^2 (1+\xi_{Ges}) - 1}{2g}}}_{k} \cdot \frac{dz}{\sqrt{h+z}}$$

$$= k \cdot 2\sqrt{h+z}\,\Big|_H^0 = 2k\cdot\left(\sqrt{h}-\sqrt{h+H}\right)$$

$$= \sqrt{\frac{2}{g}\left[\left(\frac{4A}{\pi d^2}\right)^2 (1+\xi_{Ges}) - 1\right]} \cdot \left(\sqrt{h}-\sqrt{h+H}\right)$$

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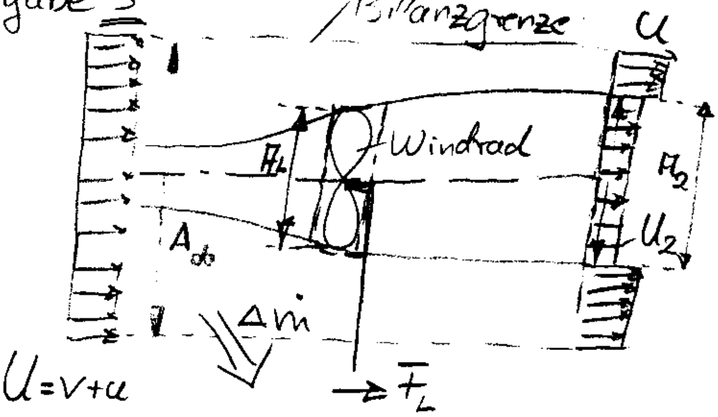
Aufgabe 3

a)



Massenstrom:

$$-\rho U A_\infty + \rho U (A_\infty - A_2) + \rho U_2 A_2 + \Delta\dot m = 0$$

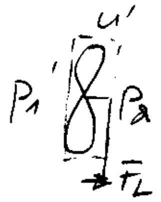
$$\Rightarrow \Delta\dot m = \rho A_2 (U - U_2)$$

Impulssatz: $-\rho U^2 A_\infty + \rho U^2 (A_\infty - A_2) + \rho A_2 U_2^2 + \Delta\dot m U = F_L$

mit $\Delta\dot m = \ldots$

$$\Rightarrow \rho A_2 U_2 (U_2 - U) = F_L \quad *$$

Impulssatz um Windrad:



$$-\rho u'^2 A_L + \rho u'^2 A_L = (p_1' - p_2') A_L + F_L$$

Bernoulli: $p_1' - p_2' = \left(p_\infty + \frac{\rho}{2}(U^2 - u'^2)\right) - \left(p_\infty + \frac{\rho}{2}(U_2^2 - u'^2)\right)$

$$\Rightarrow F_L = -\frac{\rho}{2}(U^2 - U_2^2) A_L \quad **$$

* und ** gleichsetzen:

$$-\frac{\rho}{2}(U^2 - U_2^2) A_L = \rho A_2 U_2 (U_2 - U) \; ; \text{Konti: } \rho A_L u' = \rho A_2 U_2$$

$$\Rightarrow \frac{1}{2}(U + U_2) = A_2 U_2 = A_L u'$$

$$\Rightarrow u' = \frac{U + U_2}{2}$$

$$P_L = -F_L \cdot u' = \frac{\rho}{4} U^3 \left(1 - \left(\frac{U_2}{U}\right)^2\right)\left(1 + \frac{U_2}{U}\right) A_L \; ; \; \frac{U_2}{U} = \xi$$

$$= \frac{\rho}{4} U^3 A_L (1 - \xi^2)(1 + \xi)$$

$$\frac{\partial P}{\partial \xi} \overset{!}{=} 0 = \frac{\rho}{4} U^3 A_L \underbrace{\left((1+\xi)(-2\xi) + 1 - \xi^2\right)}_{=0}$$

$$\Rightarrow \xi_{1,2} = -\frac{1}{3} \pm \sqrt{\frac{1}{9} + \frac{3}{9}} = -\frac{1}{3} + \frac{2}{3}$$

$$\Rightarrow \xi = 1/3$$

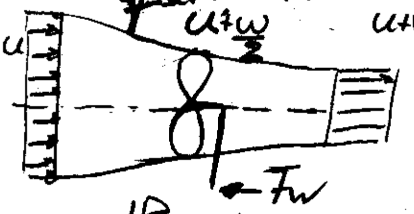
$$\Rightarrow P_{L,opt} = -F_{L,opt}\cdot u_{,opt} = -F_{L,opt}\cdot \frac{2}{3}U = \frac{8}{27}\rho U^3 A_L$$

$$F_{opt} = -F_{L,opt} = \frac{4}{9}\rho U^2 A_L$$

b) keine mechanischen Verluste $\Rightarrow P_L + P_W = 0$

kein Widerstand vom Bootskörper $\Rightarrow F_{L,opt} + F_W = 0$

Schiffschraube:



$u+w$; w unbekannt

$$P_{L,opt} = -P_W = -\left(u+\frac{w}{2}\right)F_W = -F_L\frac{2}{3}\overbrace{(u+v)}^{=U}$$

mit $F_L = F_W$ $\Rightarrow$ $w = \frac{1}{3}(4v-2u)$

$$F_{L,opt} = \frac{4}{9}\rho_L U^2 A_L = \rho_W A_W\, w\left(\frac{u+w+u}{2}\right) = -F_W$$

$$\Leftrightarrow \frac{4}{9}\underbrace{\frac{\rho_L A_L}{\rho_W A_W}}_{=q} U^2 = w\left(2u+\frac{4}{3}v-\frac{2}{3}u\right)$$

$$= w\frac{2}{3}(u+v)$$

$$= \frac{2}{9}(4v-2u)(u+v)$$

mit $U=u+v$ folgt:

$$\frac{4}{9}q(u+v)^2 = \frac{2}{9}(4v-2u)(u+v)$$

$$\Leftrightarrow 2q(u+v) = 2(2v-u)$$

$$\Leftrightarrow u = \frac{2-q}{1+q}\cdot v$$

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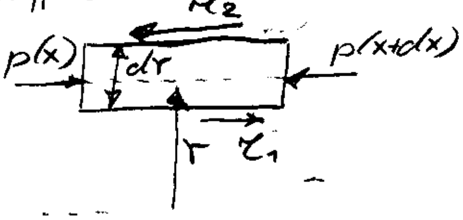
Aufgabe 4

a) Geschwindigkeitsverteilung:

IES am diff. Volumenelement:



$$0 = \tau_1 2\pi\left(r-\frac{dr}{2}\right)dx - \tau_2 2\pi\left(r+\frac{dr}{2}\right)dx$$
$$p(x)2\pi r\,dr - p(x+dx)2\pi r\,dr$$

$$\Rightarrow 0 = -\underbrace{\left(\tau + r\frac{d\tau}{dr}\right)} - r\frac{dp}{dx}$$

$$\Rightarrow \frac{d(r\cdot\tau)}{dr} = -r\frac{dp}{dx}$$

1. Integration:

$$\tau\cdot r = -\frac{dp}{dx}\frac{r^2}{2} + C_1$$

$$\Leftrightarrow \tau = -\frac{dp}{dx}\frac{r}{2} + \frac{C_1}{r}$$; mit R.B. $\tau(r=0)=0$ folgt $C_1 = 0$

$$\Rightarrow \tau(r) = -\frac{dp}{dx}\frac{r}{2} = -\eta\frac{du}{dr}$$ (Newtonsche Fließgesetz)

$$\Leftrightarrow \frac{du_2}{dr} = \frac{r}{2\eta}\frac{dp}{dx}$$

2 Integration:

$$u_2(r) = \frac{1}{4\eta}\frac{dp}{dx}\cdot r^2 + C_2$$; mit R.B. $u(r=R)=0$ folgt $C_2 = -\frac{R^2}{4\eta}\frac{dp}{dx}$

$$\Rightarrow u_2(r) = -\frac{R^2}{4\eta}\frac{dp}{dx}\left(1-\left(\frac{r}{R}\right)^2\right)$$

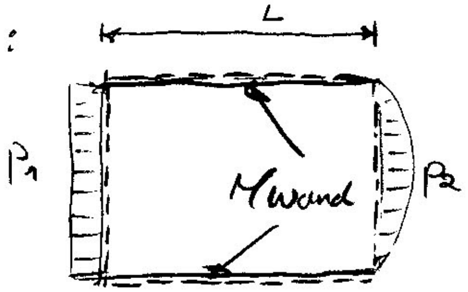
$\frac{dp}{dx} = ?$

$$\dot{Q} = \text{konst} = u_1\pi R^2 = 2\pi R^2\int_0^1 u_2(r/R)\frac{r}{R}\,d\left(\frac{r}{R}\right)$$

$$= -\frac{R^4}{8\eta}\frac{dp}{dx} \Rightarrow \frac{dp}{dx} = -\frac{8u_1}{R^2}\eta$$

$$\Rightarrow u_2(r) = 2u_1\left(1-\left(\frac{r}{R}\right)^2\right)$$

b) IES :



$$-\dot{I}_{Ein} + \dot{I}_{aus} = \Delta p \pi R^2 - F_R$$

mit $\Delta p = p_1 - p_2$

$$F_R = \frac{1}{2}\left(\tau_{Wand}(x=0) + \tau_{Wand}(x=L)\right) 2\pi R L$$

$$\tau_{wand}(x=L) = -\eta \left.\frac{du_2}{dr}\right|_{r=R} = 4\eta \frac{u_1}{R}$$

$$\tau_{wand}(x=0) = C \cdot \tau_w(x=L)$$

$$\Rightarrow F_R = \tau_{wand}(x=L) \cdot (C+1) \pi R L$$

$$\dot{I}_{Ein} = -\rho u_1^2 \pi R_1^2$$

$$\dot{I}_{aus} = 2\pi \rho R^2 \int_0 u_2\left(\frac{r}{R}\right)^2 \frac{r}{R} \, d\left(\frac{r}{R}\right)$$

$$= \frac{4}{3} \pi R^2 \rho u_1^2$$

$$\Rightarrow \quad \rho \frac{u_1^2 \pi R^2}{3} = \Delta p \pi R^2 - \pi R L (C+1) 4\eta \frac{u_1}{R}$$

$$\Leftrightarrow \Delta p = 4\eta \frac{u_1 L (C+1)}{R^2} + \rho \frac{u_1^2}{3}$$

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A5)

a) Einflußgrößen: $g, u_\infty, \rho, \eta, h, f$

Dimensionen: m, s, kg

$\Rightarrow k = 6, r = 3 \Rightarrow k - r = 3$ Kenngrößen

b) Wiederkehrende Variable

u_∞, h, ρ

$$\Pi_1 = g \cdot u_\infty^{\alpha_1} \cdot h^{\beta_1} \cdot \rho^{\gamma_1}$$

$[m]: \quad 1 + \alpha_1 + \beta_1 - 3\gamma_1 = 0$

$[kg]: \quad 0 + 0 + 0 + \gamma_1 = 0 \Rightarrow \gamma_1 = 0$

$[s]: \quad -2 - \alpha_1 + 0 + 0 = 0 \Rightarrow \alpha_1 = -2$

$\Rightarrow \beta_1 = 1$

$$\Pi_1 = \frac{g \cdot h}{u_\infty^2} = \frac{1}{Fr^2}$$

$$\Pi_2 = \eta \cdot u_\infty^{\alpha_2} h^{\beta_2} \rho^{\gamma_2}$$

$[m]: \quad -1 + \alpha_2 + \beta_2 - 3\gamma_2 = 0$

$[kg]: \quad 1 + 0 + 0 + \gamma_1 = 0 \Rightarrow \gamma_2 = -1$

$[s]: \quad -1 - \alpha_2 + 0 + 0 = 0 \Rightarrow \alpha_2 = -1$

$\Rightarrow \beta_2 = -1$

$$\Pi_2 = \frac{\eta}{u_\infty h \rho} = \frac{1}{Re}$$

$$\Pi_3 = f \cdot u_\infty^{\alpha_3} h^{\beta_3} \rho^{\gamma_3}$$

$$[m]: \quad 0 + \alpha_3 + \beta_3 - 3\gamma_3 = 0$$

$$[kg]: \quad 0 + 0 + 0 + \gamma_3 = 0 \Rightarrow \gamma_3 = 0$$

$$[s]: \quad -1 - \alpha_3 + 0 + 0 = 0 \Rightarrow \alpha_3 = -1$$

$$\Rightarrow \beta_3 = 1$$

$$\Pi_3 = \frac{f \cdot h}{u_\infty} = Sr$$

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Aufgabe 6:

a) $z + \frac{v^2}{2g} = H$, Neigung wird vernachlässigt!

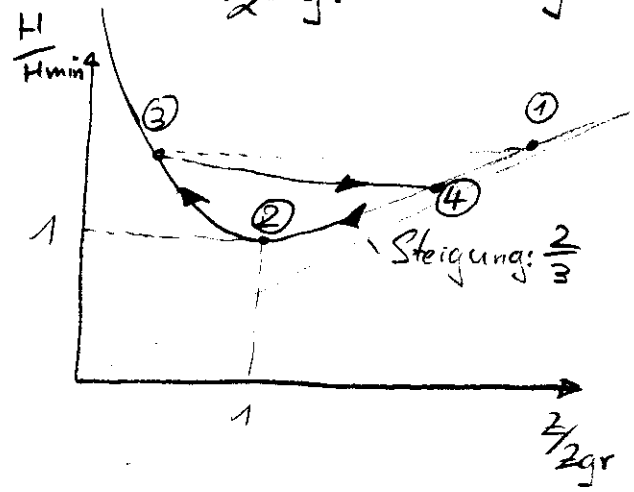
mit $\dot{Q} = zBv$ folgt: $H = z + \frac{\dot{Q}^2}{2gB^2z^2}$;

H_{min}, z_{gr}: $\frac{dH}{dz} \overset{!}{=} 0 = 1 - \frac{\dot{Q}^2}{gB^2 z_{gr}^3} \Leftrightarrow z_{gr} = \sqrt[3]{\frac{\dot{Q}^2}{gB^2}}$

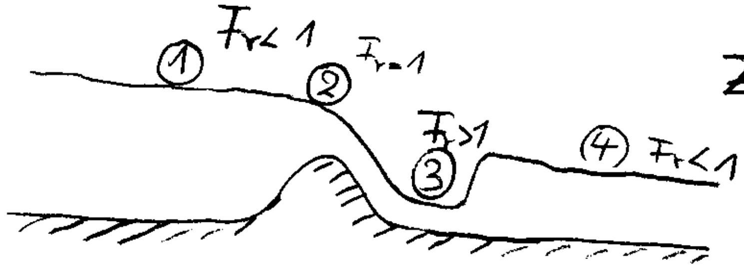
$$\Rightarrow H_{min} = H(z_{gr}) = z_{gr} + \frac{\dot{Q}^2}{2g z_{gr}^2 B^2}$$

$$= z_{gr} + \frac{1}{2}\frac{z_{gr}^3}{z_{gr}^2} = \frac{3}{2} z_{gr}$$

$$\Rightarrow H/H_{min} = \frac{z + \frac{\dot{Q}^2}{2gz^2B^2}}{\frac{3}{2} z_{gr}} = \frac{2}{3}\frac{z}{z_{gr}} + \frac{1}{3}\left(\frac{z}{z_{gr}}\right)^{-2}$$



b)



Zustandsänderungen siehe Skizze zu a)

c) z_3: $H_1 = H_3 = z_1 + \frac{\dot{Q}^2}{2gB^2z_1^2} = z_3 + \frac{\dot{Q}^2}{2gB^2z_3^2}$

$$\Leftrightarrow z_1 - z_3 = \frac{\dot{Q}^2}{2gB^2}\left(\frac{1}{z_3^2} - \frac{1}{z_1^2}\right) = \frac{\dot{Q}^2}{2gB^2}\frac{(z_1+z_3)(z_1-z_3)}{z_1^2 z_3^2}$$

$$\Rightarrow z_3 = \frac{\dot{Q}^2}{4gB^2z_1^2} \pm \sqrt{\left(\frac{\dot{Q}^2}{4gB^2z_1^2}\right)^2 + \frac{\dot{Q}^2}{2gB^2z_1}}$$

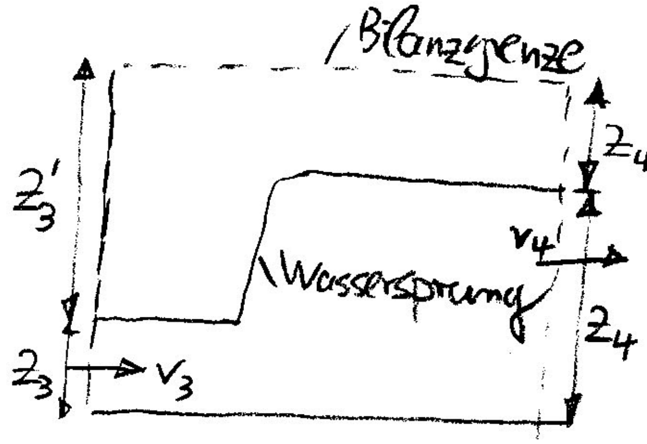
$$\Rightarrow Fr_3 = \frac{v_3}{\sqrt{gz_3}} = \frac{\dot{Q}}{B\sqrt{gz_3^3}}$$

$$H_3 = H_1 = z_3 + \frac{\dot{Q}^2}{2gB^2 z_3^2}$$

$y_w + H_{min} = H_1$; mit $H_{min} = \frac{3}{2} z_{gr}$; $z_{gr} = \sqrt[3]{\frac{\dot{Q}^2}{gB^2}}$

$$\Longrightarrow H_1 - \tfrac{3}{2} z_{gr} = z_1 + \frac{\dot{Q}^2}{2gB^2 z_1^2} - \frac{3}{2} z_{gr}$$

d)



Kontí: $\rho z_3 v_3 = \rho z_4 v_4$

$$\Longrightarrow v_4 = v_3 \frac{z_3}{z_4}$$

Impulssatz in x-Richtung über Wassersprung

$$-\rho z_3 v_3^2 B + \rho z_4 v_4^2 B = p_a B z_3' + B\int_0^{z_3} (p_a + \rho g z)\,dz - p_a B z_4' - B\int_0^{z_4} (p_a + \rho g z)\,dz$$

$$\Longrightarrow -z_3 v_3^2 + z_4 v_3^2 \left(\frac{z_3}{z_4}\right)^2 = \frac{g}{2}\left(z_3^2 - z_4^2\right)$$

$$\Longleftrightarrow z_{4\,1/2} = -\frac{1}{2} z_3 \pm \sqrt{\frac{1}{4} z_3^2 + \frac{2 v_3^2 z_3}{g}}$$

$$\Longrightarrow \Delta H \overset{\text{mit } H_1 = H_3}{=} z_1 - z_4 + \frac{\dot{Q}^2}{2gB^2}\left(\frac{1}{z_1^2} - \frac{1}{z_4^2}\right)$$

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Aufgabe 7

a) Koeffizienten a_0, a_1, a_2, a_3

① $y=0 \;:\; u=0 \Rightarrow a_0 = 0$

② $y=\delta \;:\; u=U \Rightarrow 1 = \cancel{a_0}^{0} + a_1 + a_2 + a_3$

③ $y=0 :\; -v\frac{\partial u}{\partial y} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \frac{\eta}{\rho}\frac{\partial^2 u}{\partial y^2}$

mit $v = \frac{Q}{BL} = c_Q U \;;\; \frac{\partial p}{\partial x} = 0$

$$\Rightarrow -\frac{a_1}{\delta} c_Q U = \frac{\eta}{\rho}\frac{2a_2}{\delta^2}$$

$$\Leftrightarrow a_1 = -\frac{\eta}{\rho}\frac{2a_2}{\delta c_Q U}$$

④ $y=\delta :\; \frac{\partial u}{\partial y} = 0 \;:\; 0 = a_1 + 2a_2 + 3a_3$

3·② − ④ ergibt: $3 = 2a_1 + a_2$

mit ③ folgt: $3 = -\frac{\eta}{\rho}\frac{4a_2}{\delta c_Q U} + a_2 = a_2\left(1 - \frac{4\eta}{\rho\delta c_Q U}\right)$

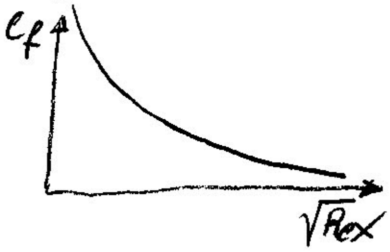
$$\Leftrightarrow a_2 = \frac{3\rho\delta c_Q U}{\rho\delta c_Q U - 4\eta}$$

$$a_1 = -\frac{6\eta}{\rho\delta c_Q U - 4\eta}$$

$$a_3 = 1 - a_1 - a_2 = -\frac{2(\rho\delta c_Q U - \eta)}{\rho\delta c_Q U - 4\eta}$$

b) $\frac{\delta_{99}(x)}{x} = C \cdot \frac{1}{\sqrt{Re_x}}$; mit $C = 4{,}9$ siehe Vorlesungsskript

c) $c_f = \frac{0{,}664}{\sqrt{Re_x}}$



d) $Re_{krit} \approx 500000$

beeinflussende Größen u.a. -Oberflächenrauigkeit,
-Störungen in der freien Anströmung

Aufgabe 8

a) Konti : $\dot{m} = \rho u A = konst$; $d\dot{m} = 0 = d\rho\, uA + \rho\, du A + \rho u dA$

$$\Longrightarrow \frac{d\rho}{\rho} + \frac{du}{u} + \frac{dA}{A} = 0$$

Impuls: $u\,du = -\frac{dp}{\rho} = -\frac{dp}{d\rho}\frac{d\rho}{\rho}$

mit $c^2 = \frac{dp}{d\rho}$ folgt: $-\frac{u^2}{c^2}\frac{du}{u} + \frac{du}{u} + \frac{dA}{A} = 0$

$$\Rightarrow \frac{du}{u}(1-M^2) = -\frac{dA}{A}$$

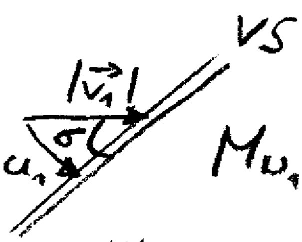
$$\Leftrightarrow \frac{du}{u} = -\frac{dA}{A}\frac{1}{1-M^2}$$

$M < 1$	$M > 1$
$dA > 0$	$dA > 0$
$\Rightarrow du < 0$	$\Rightarrow du > 0$

und jeweils umgekehrt für $dA < 0$

b) Konti über Verdichtungsstoß :

$$\frac{\rho_2}{\rho_1} = \frac{u_1}{u_2} = \frac{u_1^2}{u_1 u_2} \overset{\text{Prandtl.Bez.}}{=} \frac{u_1^2}{c^{*2}} = M_{u_1}^{*2}$$



$$M_{u_1} = \frac{u_1}{c_1} = \frac{|\vec{v}_1|}{c_1}\sin\sigma = M_1 \sin\sigma$$

mit Hinweis

$$\Rightarrow \frac{\rho_2}{\rho_1} = \frac{\gamma+1}{\gamma - 1 + \frac{2}{(M_1 \sin\sigma)^2}} \quad ; \ \sigma = 90° \text{ für } \perp \text{ VS}$$

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