Техникалық термодинамика

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Жылу мөлшері. Жылу балансының теңдеуі. cv және cp жылусиымдылықтары. Энтропия

$$dU = \left(\frac{\partial U}{\partial T}\right)_V dT + \left(\frac{\partial U}{\partial V}\right)_T dV \ .$$

$$U = \sum U_i \ . \quad u = U/m \ (\text{Дж/кг}).$$

$$Q - L = \Delta E \ ,$$

$$\Delta E = E_2 - E_1 = U_2 - U_1 + m\left(\frac{w_2^2}{2} - \frac{w_1^2}{2}\right) + mg(z_2 - z_1) \ .$$

$$\mathrm{L} = \mathrm{L_{об}} + \mathrm{L_{дв}} + \mathrm{L_{тех}} + \mathrm{L_{тр}} \ .$$

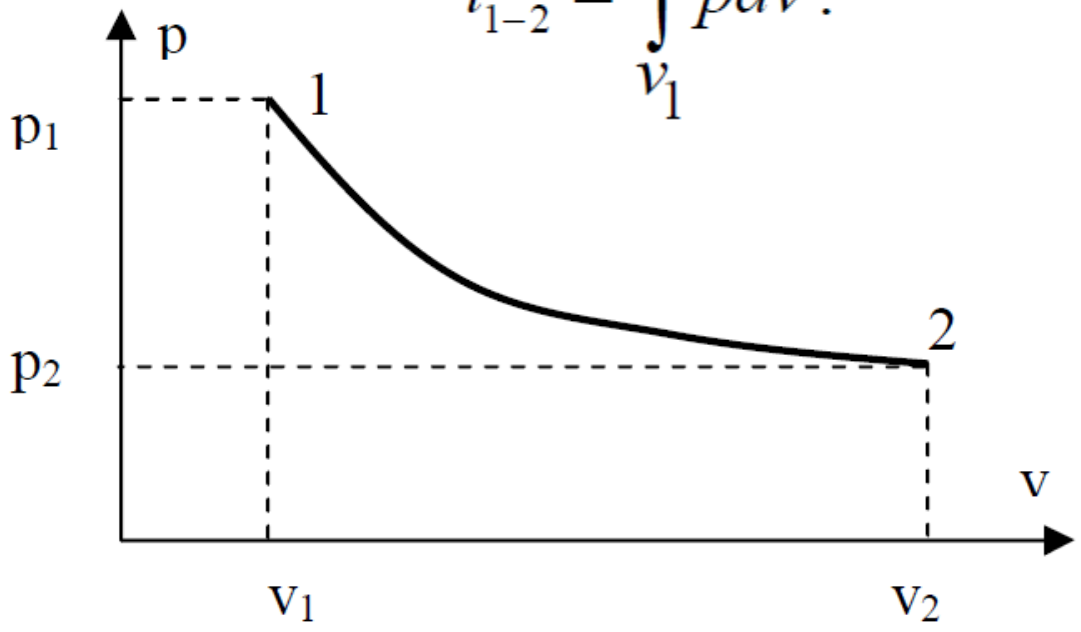
$$Q = Q_{внеш} + Q_{тр} \ .$$

$$\delta q = du + d\left(\frac{w^2}{2}\right) + gdz + l_{об} + l_{дв} + l_{тех} \ ,$$

$$\delta q = du + l_{об} \, .$$

$$\delta q = du + pdv$$

$$l_{1-2} = \int_{v_1}^{v_2} pdv \, .$$



Энтальпия

$$H = U + pV\,, \quad V=h\cdot S, \quad l=p\cdot S\cdot h=pV$$

$$\boxed{h = u + pv\,.}$$

$$\delta q = dh - vdp\,, \quad l_0 = -vdp$$

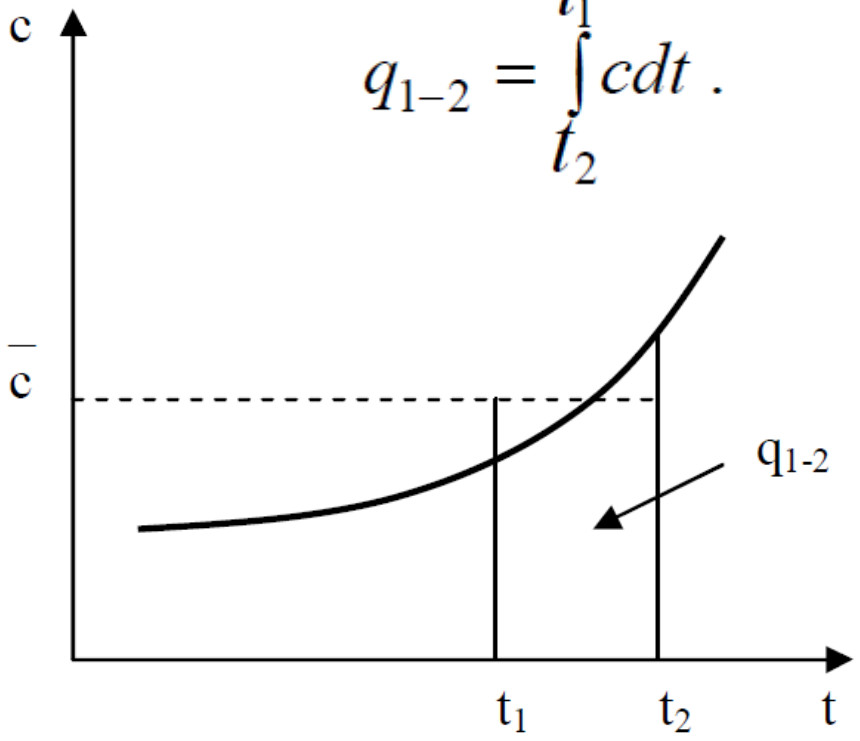
dz=0 и l_{mex}=0

$$-vdp = d\left(\frac{w^2}{2}\right)$$

Жылусыйымдылық

$$C_x = \frac{Q_x}{\Delta T}.$$

$$q_{1-2} = \int_{t_2}^{t_1} c dt .$$



$$c = a_0 + a_1 t + a_2 t^2 + \ldots \quad ,$$

$$q_{1-2} = a_0 (t_2 - t_1) + \frac{a_1}{2} (t_2{}^2 - t_1{}^2) + \frac{a_2}{3} (t_2{}^3 - t_1{}^3) + \ldots ;$$

$$\bar{c}\Big|_0^t == \frac{\int_0^t c dt}{t} \quad .$$

$$\bar{c}\Big|_{t_1}^{t_2} = \frac{\bar{c}\Big|_0^{t_2} \cdot t_2 - \bar{c}\Big|_0^{t_1} \cdot t_1}{t_2 - t_1} \quad ,$$

$$q_{1-2} = \bar{c}\Big|_{t_1}^{t_2} \cdot (t_2 - t_1) \, .$$

Теплоемкости c_v и c_p

$$c_v = \frac{\delta q_v}{dT}, \qquad c_p = \frac{\delta q_p}{dT},$$

$$\delta q = du + pdv \qquad (dv=0)\ \delta q_v = du.$$

$$c_v = \left(\frac{\partial u}{\partial T}\right)_v.$$

$$du = \left(\frac{\partial u}{\partial T}\right)_v dT + \left(\frac{\partial u}{\partial v}\right)_T dv = c_v dT$$

$$u_2 - u_1 = \int_{T_1}^{T_2} c_v dT \approx \overline{c}_v (T_2 - T_1),$$

$$\delta q = dh - vdp \qquad (dp=0)\ \delta q_p = dh.$$

$$c_p = \left(\frac{\partial h}{\partial T}\right)_p .$$

$$dh = c_p dT ,$$

$$h_2 - h_1 = \int_{T_1}^{T_2} c_p dT \approx \bar{c}_p (T_2 - T_1) ,$$

$$\delta q = c_v dT + pdv ,$$

$$\delta q = c_p dT - vdp .$$

$$(c_p - c_v)dT = pdv + vdp = d(pv) = RdT\ ,$$

$$c_p - c_v = R\ ,$$

Идеал газ қоспаларының жылусыйымдылығы

$$c_v = \sum_i g_i c_{vi}\ , \quad c_p = \sum_i g_i c_{pi}\ .$$

$$c'_v = \sum_i r_i c'_{vi}\ , \quad c'_p = \sum_i r_i c'_{pi}\ .$$

Энтропия

$$\delta q = du + \delta l = du + pdv$$

$$\frac{\delta q}{T} = \frac{c_v dT}{T} + \frac{pdv}{T} = \frac{c_v dT}{T} + R\frac{dv}{v} = d\left(\int \frac{c_v}{T} dT + R\ln v\right),$$

$$ds = \frac{\delta q}{T} \ ,$$

$$s_2 - s_1 = c_v \ln \frac{T_2}{T_1} + R \ln \frac{v_2}{v_1} ,$$

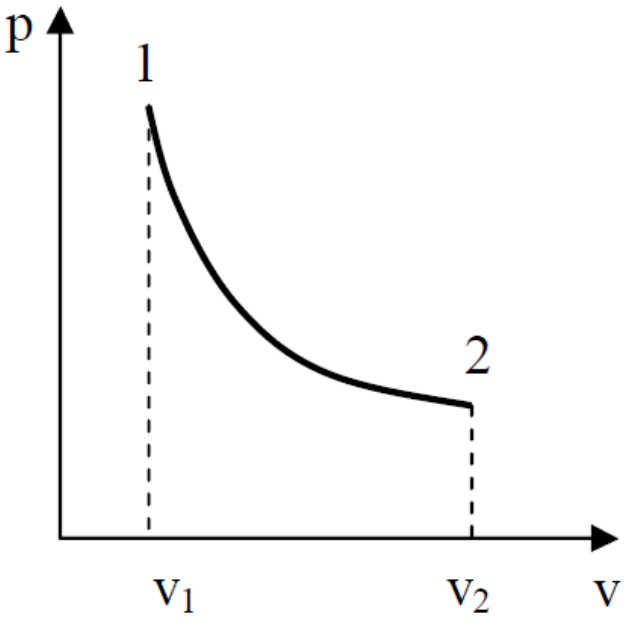
$$s_2 - s_1 = c_p \ln \frac{T_2}{T_1} - R \ln \frac{p_2}{p_1} \ .$$

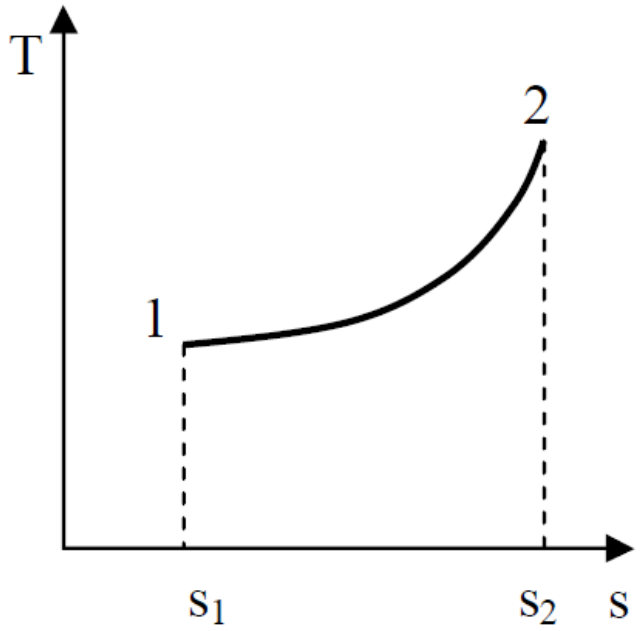
$$\delta q = Tds$$

$$Tds = du + pdv \ ,$$

$$Tds = dh - vdp \ .$$

Рабочая *pv*- и тепловая *Ts*- диаграммы





Изопроцесстер

$$pv = RT$$

$$Tds = \delta q = c_x dT \ ;$$

$$\Delta u = u_2 - u_1 = \int_{t_1}^{t_2} c_v dT = \bar{c}_v \Big|_0^{t_2} \cdot t_2 - \bar{c}_v \Big|_0^{t_1} \cdot t_1$$

$$u_2 - u_1 = c_v (t_2 - t_1) \ ;$$

$$\Delta h = h_2 - h_1 = \int_{t_1}^{t_2} c_p dT = \bar{c}_p \Big|_0^{t_2} \cdot t_2 - \bar{c}_p \Big|_0^{t_1} \cdot t_1$$

$$h_2 - h_1 = c_p (t_2 - t_1) \ ;$$

$$l = \int_{v_1}^{v_2} p dv \ ;$$

$$q_{1-2} = \int_{t_1}^{t_2} c_x dT = \bar{c}_x \Big|_0^{t_2} \cdot t_2 - \bar{c}_x \Big|_0^{t_1} \cdot t_1 \ ;$$

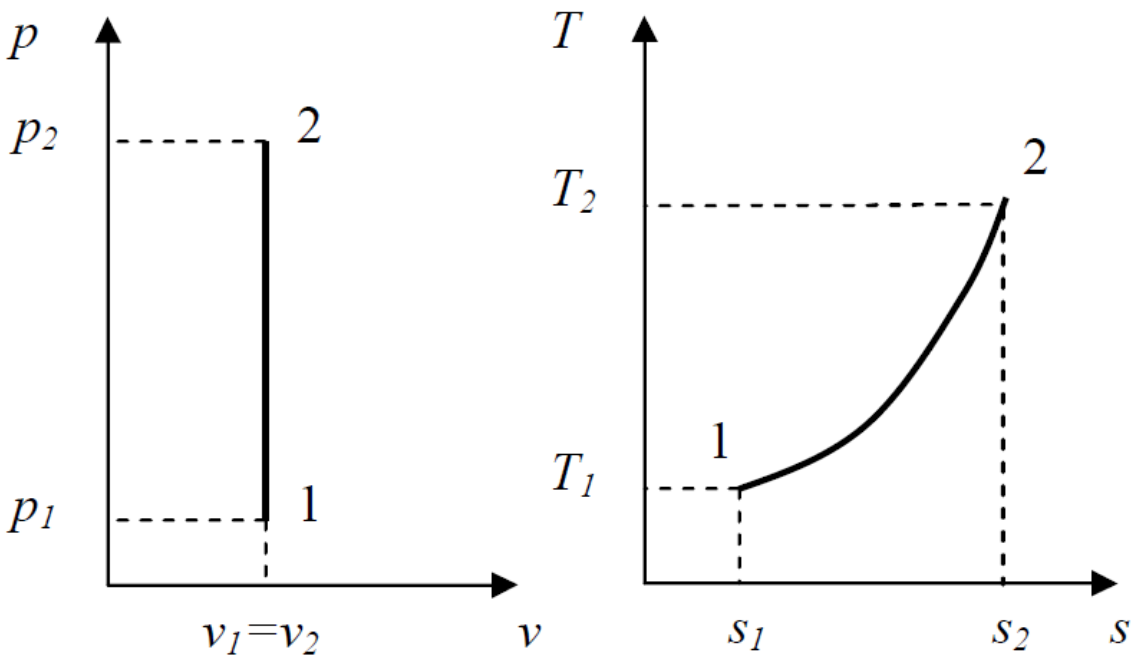
$$ds = \frac{q}{T} = \frac{du + pdv}{T} = \frac{c_v dT + \frac{RT}{v} dv}{T} = c_v \frac{dT}{T} + R \frac{dv}{v} \ ,$$

$$\Delta s = s_2 - s_1 = \bar{c}_v \Big|_{T_1}^{T_2} \ln \frac{T_2}{T_1} + R \ln \frac{v_2}{v_1} \ .$$

Изохоралық процесс

v=const $\Leftrightarrow$ $dv = 0$

$$dT = \frac{T}{c_v} ds$$



$$p_1 v_1 = RT_1\,, \quad p_2 v_2 = RT_2\,, \quad v_1 = v_2\,.$$

$$\frac{p_1}{p_2} = \frac{T_1}{T_2}\,.$$

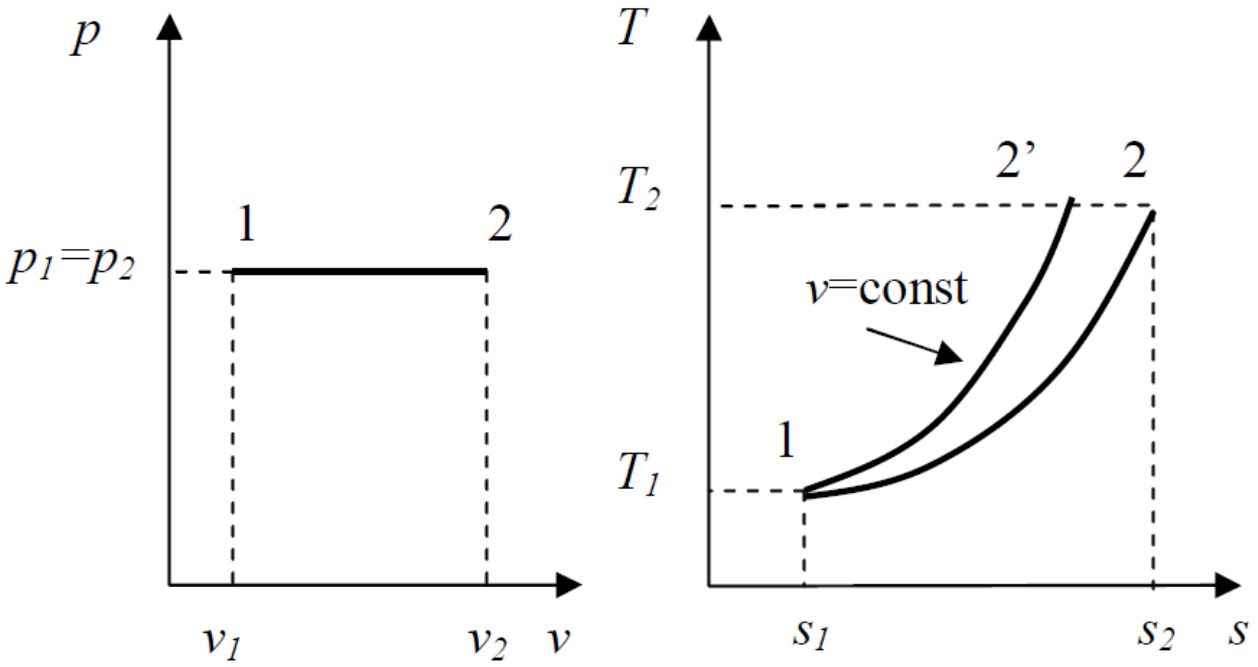
$$q_{1-2} = \int_{t_1}^{t_2} c_v dT = \bar{c}_v\Big|_0^{t_2} \cdot t_2 - \bar{c}_v\Big|_0^{t_1} \cdot t_1 = u_2 - u_1\,,$$

$$ds = \frac{\delta q}{T} = \frac{c_v dT + p dv}{T} = c_v \frac{dT}{T}\,.$$

Изобаралық процесс

$$p = const \quad \text{или} \quad dp = 0$$

$$dT = \frac{T}{c_p} ds \, .$$



$$p_1 v_1 = RT_1 , \quad p_2 v_2 = RT_2 , \quad p_1 = p_2 .$$

$$\frac{v_1}{v_2} = \frac{T_1}{T_2} .$$

$$l = p \int_{v_1}^{v_2} dv = p(v_2 - v_1) ,$$

$$q_{1-2} = \int_{t_1}^{t_2} c_p dT = \bar{c}_p \Big|_0^{t_2} \cdot t_2 - \bar{c}_p \Big|_0^{t_1} \cdot t_1 = h_2 - h_1$$

$$ds = \frac{\delta q}{T} = \frac{c_p dT - v dp}{T} = c_p \frac{dT}{T}$$

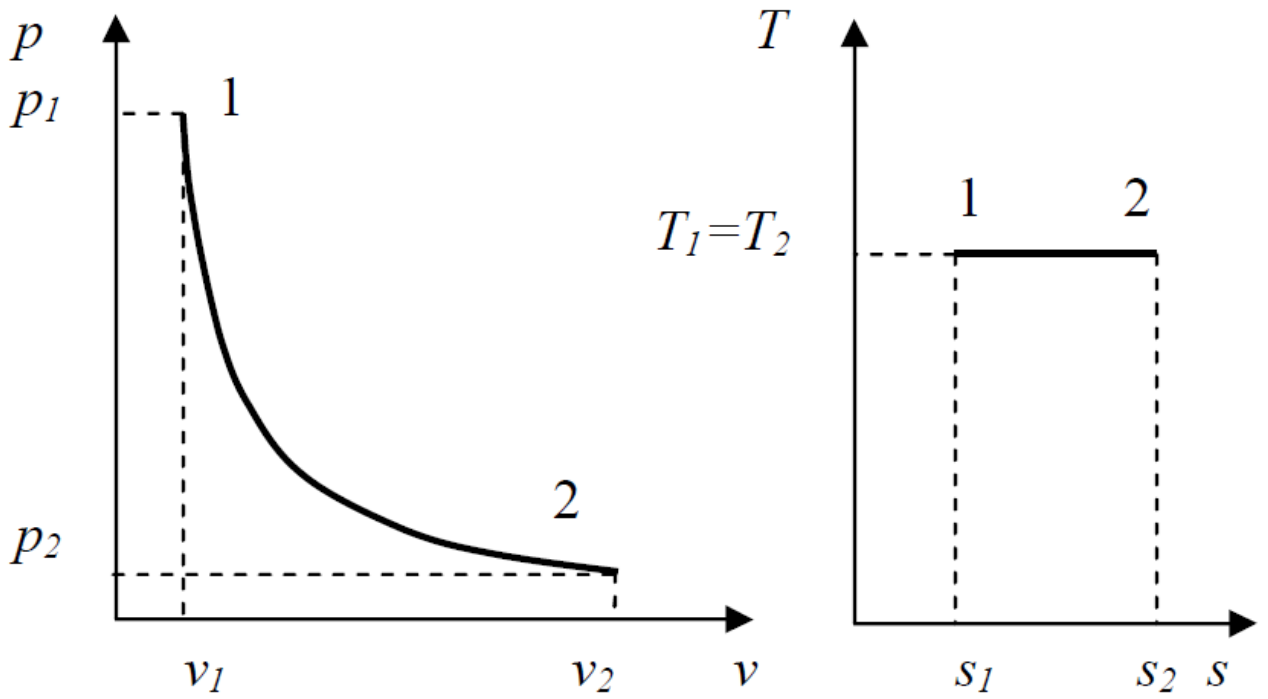
$$\Delta s = s_2 - s_1 = c_p \ln \frac{T_2}{T_1} .$$

Изотермдік процесс

$$pv=\text{const}$$

$$c_T = \frac{\delta q}{dT} = \pm\infty \qquad dT = 0$$

T=const или $dT = 0$



$$p_1 v_1 = RT_1\,, \quad p_2 v_2 = RT_2\,, \quad T_1 = T_2\,.$$

$$\frac{p_1 v_1}{p_2 v_2} = 1 \text{ или } \qquad \frac{p_2}{p_1} = \frac{v_1}{v_2}$$

$$l = RT\int_{v_1}^{v_2}\frac{dv}{v} = RT(\ln v_2 - \ln v_1) = RT\ln\frac{v_2}{v_1} = p_1 v_1 \ln\frac{p_1}{p_2}\ .$$

$$q_{1-2} = l = \int_{s_1}^{s_2} T ds = T(s_2 - s_1)\ .$$

$$ds = \frac{\delta q}{T} = \frac{c_v dT + p dv}{T} = \frac{p}{T}dv = \frac{R}{v}dv$$

$$\boxed{\Delta s = s_2 - s_1 = R\ln\frac{v_2}{v_1}\ .}$$

Адиабаталық процесс $\delta q = 0$

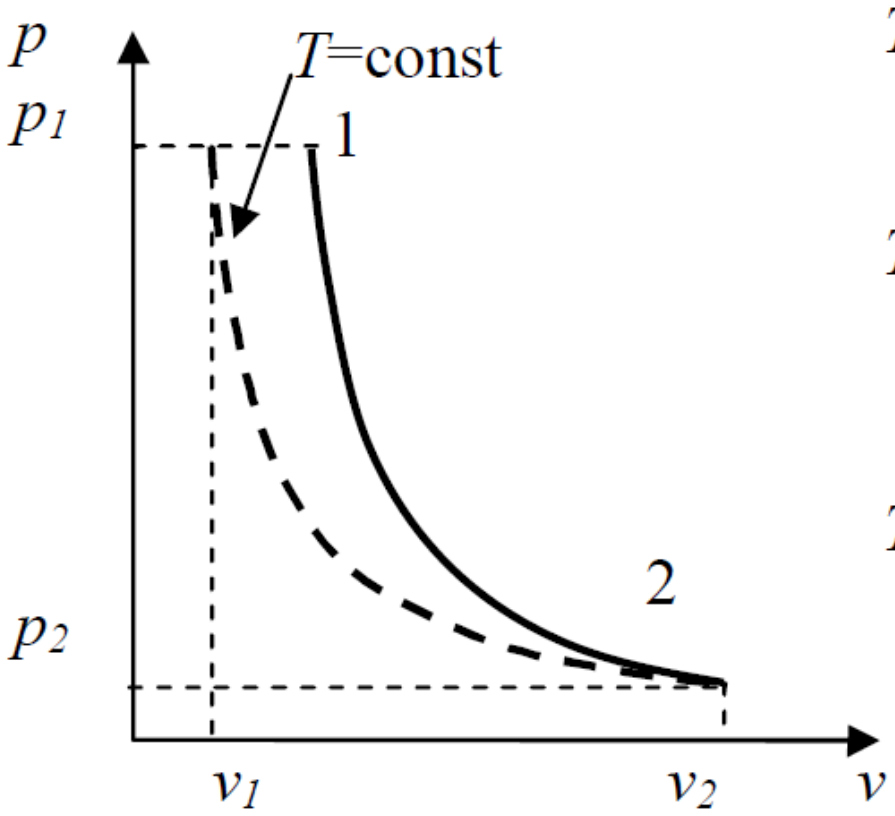
$$c_p dT - v dp = 0\,, \quad c_v dT + p dv = 0$$

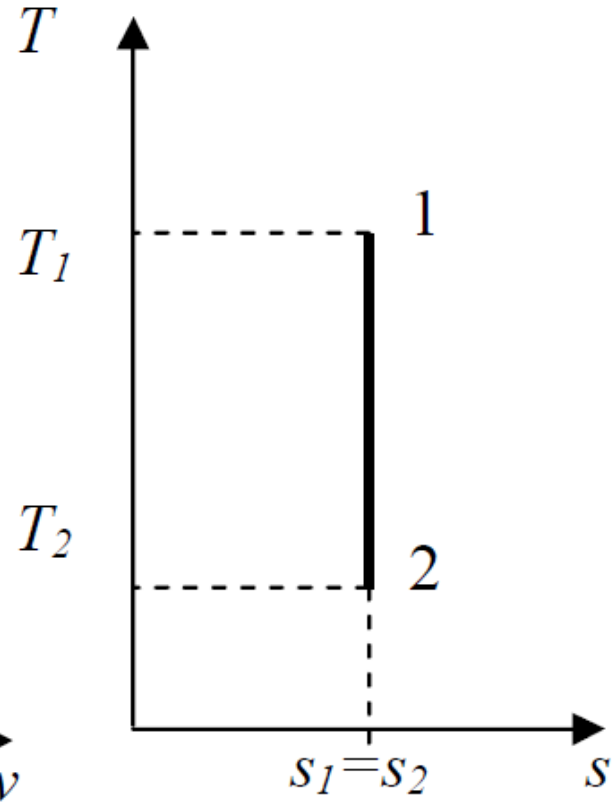
$$\frac{c_p dT}{c_v dT} = -\frac{v dp}{p dv} \quad \text{или} \quad \frac{k dv}{v} = -\frac{dp}{p}$$

$$k \ln v + \ln p = \text{const}$$

$$p v^k = \text{const} \qquad (k = c_p / c_v > 1)$$

$$c = \delta q / dT = 0$$





$$\frac{p_1}{p_2}=\left(\frac{v_2}{v_1}\right)^{k},\quad \frac{v_2}{v_1}=\left(\frac{p_1}{p_2}\right)^{1/k},\quad \frac{T_2}{T_1}=\left(\frac{p_2}{p_1}\right)^{(k-1)/k}=\left(\frac{v_1}{v_2}\right)^{k-1}.$$

$$l = \int_{v_1}^{v_2} p dv = \int_{v_1}^{v_2} \frac{p_1 v_1^k}{v^k} dv = \frac{p_1 v_1^k}{1-k}\left(v_2^{1-k} - v_1^{1-k}\right) = \frac{1}{k-1}\left(p_1 v_1 - p_2 v_2\right) =$$

$$= \frac{p_1 v_1}{k-1}\left(1 - \frac{T_2}{T_1}\right) = \frac{R}{k-1}\left(T_1 - T_2\right).$$

$$q_{1-2} = 0\,.$$

$$\Delta s = s_2 - s_1 = 0$$

Политроптық процесс

$$pv^n = \text{const}$$

- изохорный процесс соответствует политропному при $n=\pm\infty$;
- изобарный – $n=0$;
- изотермический – $n=1$;
- адиабатный – $n=k=\text{const}$.

$$p_1 v_1^n = p_2 v_2^n, \quad \left(\frac{v_1}{v_2}\right)^n = \frac{p_2}{p_1},$$

$$n = \frac{\ln\left(\frac{p_2}{p_1}\right)}{\ln\left(\frac{v_1}{v_2}\right)}.$$

$$c_n = \delta q / dT$$

$$dT = \frac{T}{c_n} ds$$

$$\frac{p_1}{p_2} = \left(\frac{v_2}{v_1}\right)^n, \quad \frac{v_2}{v_1} = \left(\frac{p_1}{p_2}\right)^{1/n}, \quad \frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{(n-1)/n} = \left(\frac{v_1}{v_2}\right)^{n-1}.$$

$$l = \frac{1}{n-1}\left(p_1 v_1 - p_2 v_2\right) = \frac{p_1 v_1}{n-1}\left(1 - \frac{T_2}{T_1}\right) = \frac{R}{n-1}\left(T_1 - T_2\right).$$

$$q_{1-2} = \Delta u + l = c_v(T_2 - T_1) + \frac{R}{n-1}(T_1 - T_2) = \left(c_v - \frac{R}{n-1} \right)(T_2 - T_1) =$$

$$= \left(c_v - \frac{c_p - c_v}{n-1} \right)(T_2 - T_1) = c_v \frac{n-k}{n-1}(T_2 - T_1) .$$

$$q_{1-2} = c_n(T_2 - T_1) .$$

$$c_n = c_v \frac{n-k}{n-1} .$$

$$s_2 - s_1 = \int_{T_1}^{T_2} \frac{c_n}{T} dT .$$

$$s_2 - s_1 = c_n \ln \frac{T_2}{T_1} .$$