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## Termodinamika prenosa energije s stisnjениm zrakom

### Thermodynamics of Energy Transmission by Compressed Air

FRANC VIDERGAR – FRANC RUNOVČ

#### 0. UVOD

Rudniki so bili vedno veliki porabniki mehanskega dela, zato je razumljivo stalno iskanje virov, ki naj omogočajo pokrivanje potreb po vse večjih močeh.

Iznajdba, ali bolje razvoj parnega stroja do uporabne stopnje sta povzročila pravo industrijsko revolucijo v mnogih protizvodnih panogah.

Okoliščine pri rudniškem, predvsem jamskem delu so pri tem terjale določene posebnosti. Za uporabo parnega stroja v rudarstvu je bilo odločilno:

- prepoved pridobivanja pare v parnem kotlu v jamskih prostorih zaradi nevarnosti požara, velikih količin dimnih plinov pa tudi zaradi porabe kisika; pridobivanje je bilo tako omejeno samo na zemeljsko površje;

- razvod vroče pare s površja v območja jamskih delovišč ni bil mogoč.

Uporaba parnih strojev v rudnikih je bila po navedenem mogoča le na površju za pogon izvažalnih strojev, črpalk, strojev v pomožnih obratih ipd., jamska delovišča pa so ostala brez tega učinkovitega vira mehanskega dela.

Rešitev množinske oskrbe dislociranih delovišč z mehanskim delom je prinesla tehnična izvedba posredne uporabe parnega stroja, tako da je stisnjeni zrak pri normalni temperaturi okolice primeren za pogon strojev.

Agregati s kompresorji, ki so jih poganjali parni stroji, so se uporabili tudi v drugih panogah, ne samo v rudarstvu.

Za delo na jamskih deloviščih, ki jih je bilo mogoče z razvijanjem cevovodnim omrežjem tudi na velike razdalje oskrbovali s stisnjениm zrakom iz glavne kompresorske postaje na površju, so bila posebej dobrodošla vrtalna in odkopna kladiva ter motorji za transportne stroje.

Na prvem mestu je treba poudariti prednosti strojev na stisnjjen zrak:

- razmeroma preproste in cenene izvedbe pogonov, z vrtenjem in premim gibanjem ali obojnimi;
- robustne, vzdržljive in neobčutljive konstrukcije z nezahtevnimi popravili in preprostim vzdrževanjem;
- za upravljanje s samimi napravami niso potreben posebej usposobljeni strežniki;

— dobri mehanični in mehanski lastnosti, ki omogočajo dobro uporabo v podzemnih delovih, kar je pomembno za delovanje v podzemnih delovih.

#### 0. INTRODUCTION

Mines have always been great consumers of mechanical work, therefore, the steady search for sources to meet the greater power demand is understandable.

The discovery, or rather the development of the steam engine, Up to the application stage, caused a real industrial revolution in many production branches.

Here, the circumstances in which the mining works above all those underground are performed, require certain particularities. For the application of the steam engine in mining the following points were decisive:

- prohibition of steam production in a steam boiler in mines because of the danger of fire, great amounts of flue gases and because of oxygen consumption, as well. Thus, steam production has been limited to the surface only,

- hot steam supply from the surface to the underground faces of work wasn't possible.

According to the facts cited above the application of steam engines to the mines was possible on the surface of the earth to winding engines, pumps and machines in accessory plants only, whereas the mine faces of work remained without this important source of mechanical work.

The solution of supplying mechanical work in great quantities to dislocated faces of work was brought about by the technical accomplishment of indirect steam engine application so that at normal surrounding temperatures, compressed air is suitable for driving the working machines.

The aggregates, with compressors driven by steam engines, have been used not only in mining, but also in other branches.

For the work on mine faces, which by means of a ramified pipeline network could be supplied with compressed air from the main compressed air stations on the surface also to long distances, the hammer drills, pneumatic picks and engines for transportation machines were especially welcome.

Firstly, emphasis must be placed on the advantages of compressed air engines:

- comparatively simple and low-priced designs of drives with rotary and straight movement, or both;

- robust, endurable and insensitive constructions with modest repairs and simple maintenance;

— precejšnja ozziroma zadostna specifična moč;  
 — popolno eksplozijsko varno obratovanje;  
 — izrabljeni medij izboljšuje jamsko klimo.  
 Razvoj elektrotehnike je najprej omogočil zamenjavo parnega stroja za pogon kompresorja z elektromotorjem.

Takrat, verjetno pa že poprej, so spoznali, da je prenos energije s stisnjениm zrakom povezan z velikimi izgubami, saj se v delovnih strojih izrabljajo majhen delež dela, ki ga dovajamo na pogonsko gred kompresorja. Nadaljnji razvoj je prispeval k razdeljevanju električne energije do samih jamskih delovišč in zamenjavi motorjev na stisnjeni zrak z električnimi. Tudi pri vrtalni tehniki je celo na področju udarnega vrtanja prišlo do uvedbe elektrohidravličnih sklopov namesto pogonov s stisnjениm zrakom, vendar gre v tem primeru za razmeroma velike agregate.

Glede na omenjene prednosti uporabe stisnjenega zraka ostaja za jamsko rudarjenje še vedno zanimiv pogon udarnih kladiv, avtonakladalnikov, premikalnih naprav, predvsem pa za pnevmatski transport in zasip.

Prednosti morajo odtehtati predvsem ekonomski vidik, kajti po vseh izboljšavah, predvsem pa gospodarnostnih kompromisih tudi v sedanjem času lahko računamo samo z 10 do 30-odstotnim izkoristkom mehanskega dela.

#### V celotnem izkoristku:

so zajeti delni izkoristki, kakor so:

##### — Izkoristek kompresorja:

$$\eta = 0,1-0,3 \quad (1)$$

če ga definiramo kot razmerje med močjo teoretično potrebnega indikatorskega diagrama in močjo, dovedeno na gred kompresorja. Tu so zajete izgube zaradi nujnega podtlaka ob nasesavanju zraka in nadtlaka pri potiskanju zraka v rezervoar in mehanske izgube zaradi trenja v gibljivih sklopih. Vrednostni interval je naveden za pogoje, kakršni so potrebni za rudniško obratovanje.

Izkoristek razvoda upošteva dva učinka, in sicer:

— prostorninski izkoristek medija (stisnjenega zraka) zaradi netesnosti omrežja krmlilno-regulacijske opreme in priključkov:

— especially trained operators are not needed for operating the devices;  
 — a substantial or satisfactory specified power;  
 — fully explosion-proof operation;  
 — the used medium improves the mine climate.

The development of electrical engineering enabled the replacement of the steam engine with the electromotor as the compressor drive.

It was that time, that they probably came to realize that energy transportation by compressed air is connected with high losses since only a small share of work supplied to the compressor's drive shaft is fully utilized by working machines. Further development has contributed to electrical energy distribution to mine faces and to the replacement of compressed air motors with electric motors. Also in drilling engineering it lead to the introduction of electrohydraulic systems instead of compressed air drives, even in the field of impact drilling, but the question is of comparatively large aggregates in this case.

In view of the advantages of compressed air applications cited above, the drive of impact hammers, automatic loaders and shifting devices still remains interesting for underground mining, especially for pneumatic transportation and stowing.

The advantages above should compensate for the economic aspect since with the improvements and economic compromises only a 10 to 30 percent mechanical work efficiency can be reckoned on, also at the present time.

The total efficiency of:

$$\eta_k = 0,8-0,9 \quad (2)$$

comprises the partial efficiencies such as

##### — compressor efficiency:

$$\eta_v = 0,6-0,8 \quad (3)$$

defined as the ratio of the power of the theoretically required indicator diagram to the power supplied to the drive shaft of the compressor. Herein, the losses due to the indispensable underpressure at the air suction, and overpressure at air delivered into the tank, and the mechanical losses due to friction in hinged joints, are included. The value interval is given for conditions required in mine operation.

The distribution efficiency takes two effects into account:

— the volumetric efficiency of medium (compressed air) due to network leakage of the control and regulating equipment and fittings:

— Izgube delovne zmožnosti zraka zaradi tlachnih izgub. Če pri delovnem tlaku 7 bar dopustimo tlache izgube do delovnih strojev na 5 bar, je ustreznI izkoristek približno:

$$\eta_A = 0.8 \quad (4).$$

Tako je izkoristek razvoda:

$$\eta_C = \eta_V \cdot \eta_A = 0.5-0.7 \quad (5).$$

Mehanski izkoristek delovnih strojev glede na robustnost izvedb v povprečju ne more biti boljši od:

$$\eta_{md} = 0.85 \quad (6).$$

Pri delovnih strojih je pomembno da praktično ne morejo obratovati z minimalno polnitvijo, ampak mora biti le-ta med 70 in 100 odstotki, s čimer je izkoristek stisnjenega zraka:

$$\eta_{Ad} = 0.6-0.8 \quad (7).$$

S tem pa je izkoristek v delovnih strojih:

$$\eta_d = \eta_{md} \cdot \eta_{Ad} = 0.5-0.7 \quad (8).$$

Pojasnila:

V posameznih kompresorskih postajah rudniških obratov še vedno obratujejo tako starI kompresorji, še iz desetletij prve polovice stoletja, kakor tudi novejšI izdelki, podobno velja tudi za druge agregate kompresorskih instalacij. Glede na to je primerno navajanje podatkov v intervalih.

Koristni učinki oziroma izkoristki praktično nikoli niso navedeni v oblikI, ki bi ustrezala našemu namenu, zato jih je na primerni zapis treba še prevesti.

Izhodiščne podatke povzemanamo po enem od standardnih priručnikov, ki ga svetovno tehnično rudarstvo upošteva in ga praksa potruje [1].

— Navedba celotnega izkoristka vložene energije 0,125–0,143 (1/7–1/8) spada v spodnjo polovico intervala (1), ki smo ga dobili kot zmnožek vseh definiranih izkoristkov.

— Prostorninske izgube medija naj bi bile v povprečju 35-odstotne. Če je dobava zraka do delovnih strojev po pretežno varjenih cevovodih, so izgube seveda manjše. Glede na navedbe in praktične izkušnje izberemo izkoristek v intervalu po enačbi (3).

— lessening of working capacity of air due to pressure losses. If, at a working pressure of 7 bar, a decrease of pressure loss to 5 bar is permitted as far as the working machines, the corresponding efficiency is about

Thus, the distribution efficiency is:

$$\eta_C = 0.5-0.7 \quad (5).$$

In view of the robustness of the working machines their mechanical efficiency cannot be higher than:

$$\eta_{md} = 0.85 \quad (6).$$

on average.

With the working machines it is important that practically they cannot practically operate at the minimum charge, but should operate between 70 and 100 percent by which the compressed air efficiency is:

$$\eta_{Ad} = 0.6-0.8 \quad (7).$$

and herewith the efficiency of working machines becomes:

$$\eta_d = \eta_{md} \cdot \eta_{Ad} = 0.5-0.7 \quad (8).$$

Explanations:

In particular mine compressor stations both old compressors, from the first half of this century and the newer ones, are still in operation. A similar statement can be made for other aggregates of compressor installations. In view of this the data quotation in intervals is suitable. The effective outputs or efficiency are practically not given yet in a form corresponding to our purpose, therefore they must still be translated to a convenient form.

The starting data is assumed according to one of the standard manuals considered by the world of mining engineering and confirmed by the practice [1].

— The quotation of total input energy efficiency 0,125–0,143 (1/7–1/8) belongs to the lower half of the interval (1) obtained as the product of all defined efficiencies.

The medium volume losses should be 35-percent on average. If the air is predominantly supplied through welded pipelines to working machines, the losses are lower, of course. With respect to the quotations and practical experience the efficiency is chosen in the interval as quoted in equation (3).

— Delovnim strojem je treba zagotoviti tlak v višini vsaj 5 bar. Običajno so v rudarstvu razdalje med mestom pridobivanja stisnjene zraka in mestom porabe tudi nekaj km, zato je navedeni podatek osnovna zahteva za ureditev ustreznega razvodilšča. Če je ekspanzijsko delo zraka s tlakom 7 bar 100-odstotno, je zmogljivost zraka s tlakom 5 bar samo okoli 80 odstotkov (4).

— Po podatku, da delovni stroji porabijo za 1 kWh 55–70 m<sup>3</sup> nasesanega zraka v normalnih razmerah je, ob upoštevanju začetnega tlaka 5 bar, mehanskega izkoristka in tudi delnih izgub medija v samih strojih, tolikšna poraba mogoča, če je polnitve 100-odstotna. Če med delovne stroje vključimo tudi instalacije za pnevmatski transport in zasip, pri katerih je del ekspanzije le v cevovodu, je optimistično mogoče predvideti tudi 70-odstotno polnitve. Če je politropna ekspanzijska delovna sposobnost zraka s tlakom 5 bar pri minimalni polnitvi 1, je pri 70-odstotni polnitvi 0,8 in pri 100-odstotni polnitvi le 0,6. S tem je določena vrednost intervala (7).

— Za izkoristek kompresorja upoštevamo, da mora oskrba s stisnjениm zrakom ustrezati časovno zelo spremenljivi porabi in zato v večini kompresorskih postaj obratuje po več batnih kompresorjev; da so kompresorji različnih starosti pokončni in vodoravni. Mehanski izkoristek ( $\eta_m$ ) pokončnih kompresorjev je 0,90–0,95, vodoravnih pa 0,88–0,92. Če naj skupno zajamemo mehanski izkoristek kompresorjev, je ta: 0,88–0,95. Razmerje med teoretičnim diagramom  $p$ -V in indikatorskim diagramom (indicirani izkoristek  $\eta_i$ ) je 0,94–0,98. Izkoristek kompresorjev  $\eta_k = \eta_m \cdot \eta_i$  z zaokroženima mejnima vrednostima je s tem podan z enačbo (2).

Delovni stroji so razmeroma manjši in po funkciji zelo različni (npr.: vrtalna kladiva, motorji nakladalnih lopat nakladalnikov, zasipni stroji), za njihov skupni mehanski izkoristek ocenimo izkoristek, kakršen velja za majhne kompresorje [2] in takega navajamo v enačbi (6).

Pri pridobivanju stisnjene zraka ne upoštevamo izkoristka morebitnega mehanskega prenosa (pogonski motor – kompresor), pa tudi ne električnega izkoristka pogonov, zato se v enačbi (1) navedeni izkoristek nanaša na izkoristek moči, ki je dovedena na gredi kompresorjev.

V vseh navedenih izkoristkih pa ni zajet termodinamični izkoristek celotnega procesa, ki je predmet tega članka in ga želimo kakovostno in kolikostno nedvoumno določiti.

Ob stalnem prizadevanju po zniževanju izdelavnih stroškov je razumljivo, da tam, kjer je uporaba stisnjene zraka nujno potrebna, posebej bode v oči njegova izredno velika energijska razslipnost.

— A pressure of at least 5 bar should be ensured to working machines. The distances between the place of compressed air production and that of its consumption are usually several km long, therefore, the cited data is a basic requirement for arranging a corresponding distribution system. If the expansion work of air at a pressure of 7 bar is 100 %, the capacity of air at a pressure of 5 bar is only about 80 % (4).

— According to data, 55 to 70 m<sup>3</sup> of air sucked up in normal conditions is consumed by working machines for 1 kWh; taking into account the initial pressure of 5 bar, mechanical efficiency and also partial medium losses in the machines themselves, the consumption of such weight is possible, if the charge is 100 percent. If also the pneumatic transportation and stowing installations, in which the expansion occurs in pipelines only, are numbered among to working machines, a 70-percent charge can also be optimistically anticipated. If the polytropic expansion working capacity of air at a pressure of 5 bar is 1 a minimum charge, it is 0.8 at 70 percent charge, and only 0.6 at a 100 percent charge. By this the value of the interval (7) is determined.

— As for compressor efficiency, the fact that the compressed air supply must correspond to the high consumption variations with time and that, for this reason, several reciprocating compressors operate in the majority of the compressed air stations, is taken into account and so is the fact that the compressors of different ages are either upright or horizontal. The mechanical efficiency ( $\eta_m$ ) of the upright compressors is 0.9–0.95, and that of the horizontal ones is 0.88–0.92. The mechanical efficiency of all compressors together is 0.88–0.95. The ratio of the theoretical  $p$ -V diagram to the indicator diagram (the indicated efficiency  $\eta_i$ ) is 0.94–0.98. Thus, the compressors efficiency  $\eta_k = \eta_m \cdot \eta_i$  with the two limit values rounded up is given by the equation (2).

The working machines are comparatively small and intended for various functions (e.g. hammer drills, motors of mechanical shovels and loaders). Their total mechanical efficiency is considered to be that of small compressors [2], and as such is given in equation (6).

In compressed air production the efficiency of eventual mechanical transmission (drive motor-compressor) is not taken into account and neither is the electrical efficiency of drives. Therefore, the efficiency given in equation (1) is related to the efficiency of power supplied to the compressor shaft.

But the thermodynamic efficiency of the whole process which is the subject of this paper and whose quality and quantity we wish to unambiguously determine, is not included in all the efficiencies cited above. At constant efforts are made to lower to production costs it is understandable, that in places where compressed air is indispensable the extraordinarily high waste of energy

Z vsemi mogočimi ukrepi se poskuša zvečati izkoristek celotne instalacije. Posebej v zadnjem času je slišati mnenje uporabnikov in s tem porajajoče upanje, da bi bilo z računalniškim vodenjem mogoče doseči imenitno gospodarno izboljšanje.

Nadaljnje natančno definiranje termodinamičnih razmer s kolikostno oceno, kakršne so navedene za izkoristke v (2) do (8), ima končni cilj, da bomo analizirali, kje še lahko pričakujemo kakšno izboljšavo in v kolikšni meri.

## 1. TERMODINAMIČNI PROCESI

Termodinamični proces komprimiranja, razvoda in porabe zraka želimo izločiti od drugih vplivov, s tem bomo lahko tudi termodinamični izkoristek celotnega procesa določili kot elementarni izkoristek, ki izhaja iz naravnih danosti, brez kakršnihkoli dodatkov, ki pogosto povzročajo zmedo in dvoumnost.

Prehod na čisto termodinamični proces jemljemo kakor, da se vse delovne faze odvijajo brez kakršnihkoli izgub, tako snovnih kakor energijskih zaradi mehanskega trenja in uporov. S tem prevzemamo, da so vrednosti vseh poprej definiranih izkoristkov (2) do (8) enake 1.

Tako izloženi proces bi bil načelno lahko tudi termodinamično povračljiv, zato bomo v nadaljevanju analizirali tudi tako, vsaj teoretično in primerjalno pomembno domnevo.

### 1.1 Povračljive preobrazbe

Z upoštevanjem povedanega bi bila povračljivost celotnega procesa dosežena na dva načina:

1. Kompresijo zraka od začetnega do končnega stanja bi morali dosegati po izotermi in v delovnem stroju bi morala ekspanzija potekati izotermno od končnega do začetnega stanja. S tem bi bili preobrazbi kompresije in ekspanzije po isti izotermi »naprej« in »nazaj« brez kakršnihkoli energijskih izgub. Praktično bi se morala kompresija dosegati ob izdatnem hlajenju, ekspanzija pa ob intenzivnem ogrevanju. Ker gre za izmenjavo toplotne z okolico, bi bilo zadostno hlajenje in ogrevanje mogoče le, če bi obe preobrazbi potekali zelo počasi. To pa praktično izključuje kakeršnokoli tehnično uporabo.

2. Kompresija poteka od začetnega stanja z adiabatno preobrazbo in prav tako ekspanzijo od končnega do začetnega stanja dosegamo po izentropi. Da bi bil tak proces povračljiv, bi morali biti izpolnjeni pogoji:

– pri adiabatski kompresiji se vse vloženo delo spremeni v notranjo energijo stisnjenega zraka; zato se njegova temperatura ustrezno zviša;

is particularly noticeable. Taking all the possible measures into account it is hoped that the efficiency of the whole installation will increase. Especially in recent times the opinion of consumers is that by computer conducting it would perhaps be possible to attain a remarkable economical improvement from which new hopes can arise.

The analysis of the question where and in what degree any improvement can still be expected is the final target of further specifications with quantity estimates as given for efficiencies in equations (2) to (8).

### 1. THERMODYNAMIC PROCESS

We wish to isolate the thermodynamic process of compression, distribution and consumption of air from other influences in order to determine the thermodynamic efficiency of the whole process in this way, as an elementary efficiency originating from the natural conditions free of whatever additions frequently cause confusion and ambiguity.

The transition to a pure thermodynamic process is considered as if all working phases develop free of any losses, both the matter and energy loss as well, due to mechanical friction or resistances. By this it is assumed that all efficiency values defined in equations (2) to (8) are equal to 1.

The process isolated in this way might also be thermodynamically reversible in principle, therefore, such an assumption theoretically and comparatively important at least, will also be analysed in the continuation.

### 1.1 Reversible Transformations

Taking into account all of the facts cited above the reversibility of the whole process would be attained in two ways:

1. The air compression from the initial to final state should be attained following the isotherm, and the expansion in the working machine should run isothermally from the final to initial state. Thus, the compression and expansion transformations following the same isotherm »forwards« and »backwards« would be free of any losses. Practically, the compression should be attained at efficacious cooling and the expansion at intensive heating. As previously, the question is of heat exchange with the surroundings, a satisfactory cooling or heating would only be possible if both transformations took a very slow course. This condition however, practically excludes any technical application.

2. The compression develops with adiabatic transformation from the initial to final state, and likewise, the expansion from the final to initial state is attained following the isentrope. In order for the process to be reversible the following conditions should be satisfied:

— ta visoka temperatura mora ostati konstantna pri razvodu zraka, tako da ob adiabatni ekspanziji v delovnem stroju dobimo iz notranje energije nazaj vse vloženo delo, s čimer se uporabljeni zrak vrne v prvotno stanje.

Praktično ni mogoče od začetka kompresije do konca ekspanzije vzdrževati popolno topotno izoliranost celotne naprave. S tem tudi ta različica povračljivega procesa ni tehnično izvedljiva.

## 1.2 Termodinamični prikaz dejanskega procesa

Za začetek postavitve termodinamičnega modela je primerno vzeti v določeni meri idealizirane preobrazbe, nakar bodo opravljeni popravki, da se bo model čim bolj približal stvarnosti.

Zaradi jasnosti bomo veličine ponazorili tudi kolikostno, pri čemer bomo upoštevali praktične omejitve.

Za začetno stanje vzamemo:

- prostornina  $V_1 = 1 \text{ m}^3$  zraka,
- temperatura  $T_1 = 273 \text{ K}$ ,
- tlak  $p_1 = 1.01 \text{ bar}$ ,
- gostota nasesanega zraka je s tem  $\rho_1 = 1.29 \text{ kg/m}^3$ ,
- masa zraka v procesu  $m = 1.29 \text{ kg}$ .

Iz začetnega stanja se doseže izentropna kompresija na tlak  $p_2 \approx 7 \text{ bar}$ , tako da je kompresijsko razmerje  $\epsilon = p_2/p_1 = 7$ .

Po doseženi kompresiji prevedemo zrak iz stanja »2« v stanje »3«, tako da ga pri konstantnem tlaku ohladimo na začetno temperaturo, torej:

$T_2 \rightarrow T_3 = T_1$ ; v bistvu se doseže izobarna kompresija iz stanja »2« v stanje »3«.

Ker gre domnevno za sistem brez snovnih in energijskih izgub zaradi trenja in uporov, lahko iz stanja »3« proces neposredno nadaljujemo z adiabatno ekspanzijo do stanja »4«, ki je določeno s tlakom, enakim začetnemu:  $p_4 = p_1$ . Iz stanja »4« se proces krožno vrne v začetno stanje »1«, tako da zrak pri konstantnem tlaku segrejemo na začetno temperaturo  $T_1$ , torej  $T_4 \rightarrow T_1$ , ali drugače: iz stanja »4« se doseže izobarna ekspanzija v stanje »1«.

Navedeni krožni proces v koordinatnem sistemu  $p$ - $V$  z navedbo veličin stanja ponazarja slika 1, ki v bistvu prikazuje Jouleov krožni proces [3].

Iskane vrednosti nekaterih veličin stanja ugotovimo iz znanih razmerij za izentropne spremembe stanja.

— at an adiabatic compression all input work changes in the internal energy of compressed air; therefore, its temperature increases correspondingly;

— this high temperature must remain constant in air distribution such that all input work is retrieved from the internal energy at adiabatic expansion in the working machine by which the used air is returned to its original state.

It is practically impossible to maintain a perfect heat isolation from the beginning of compression till the end of expansion. Thus, also this alternative of the reversible process is not technically practicable.

## 1.2 Thermodynamic Representation of the Actual Process

At the beginning of setting up the thermodynamic model it is convenient to take the transformations idealized to a certain degree, whereupon the corrections will be performed such that the model will as real as possible.

For clarity the magnitudes will also be represented by their quantities, whereas the practical limitations will be taken into account.

For the initial state we take:

- volume:  $V_1 = 1 \text{ m}^3$  of air
- temperature:  $T_1 = 273 \text{ K}$
- pressure:  $p_1 = 1.01 \text{ bar}$
- density of the sucked up air:  $\rho_1 = 1.20 \text{ kg/m}^3$
- mass of air in the process:  $m = 1.29 \text{ kg}$

From the initial state the isentropic compression to a pressure of  $p_2 \approx 7 \text{ bar}$  is attained such that the compression ratio becomes  $\epsilon = p_2/p_1 = 7$ .

After the attained compression the air is rendered from state »2« into state »3« so that at constant pressure it is cooled to the initial temperature, viz.:  $T_2 \rightarrow T_3 = T_1$ ;

Essentially, the isobaric compression from state »2« to state »3« is attained.

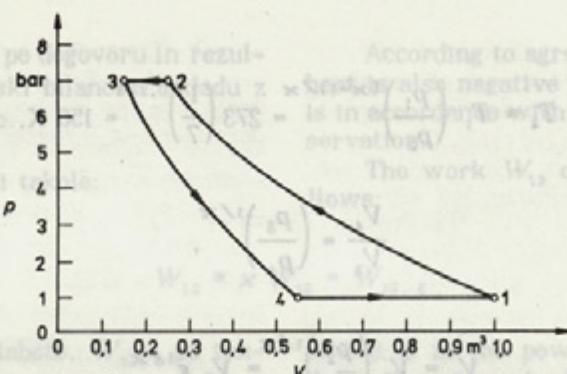
Since, supposedly, the question is of a system free of matter and energy losses due to friction and resistances, using the adiabatic expansion the process can be directly continued from state »3« to state »4« defined by a pressure that equals the initial one:  $p_4 = p_1$ . From state »4« the cyclic process reverts to the initial state »1« in such a way that at constant pressure the air is heated to the initial temperature  $T_1$ , i.e.  $T_4 \rightarrow T_1$ , or in another way: from state »4« the isobaric expansion into state »1« is attained.

The cited cyclic process in the  $p$ - $V$  coordinate system with the quotation of state quantities is illustrated in fig. 1 showing essentially the Joule cycle [3].

The values of some state quantities searched for are found from the known ratios for the isentropic state changes.

Tudi odvedena toplota je izobarno in rezultirajoča negativna in po energijski ravni z zakonom o ohranitvi energije.

Delo  $W_{12}$  pa dobimo tudi tako:



pri čemer je  $x$  eksponent adiabate in  $\varepsilon$  eksponent kompresije.

Sl. 1. Diagram p-V procesa prenosa energije s stisnjениm zrakom.  
Fig. 1. p-V diagram of the process of energy transmission by compressed air

$$\frac{T_2}{T_1} = \left( \frac{p_2}{p_1} \right)^{\frac{x-1}{x}} = \varepsilon^{\frac{x-1}{x}}$$

$$T_2 = T_1 \cdot \varepsilon^{\frac{x-1}{x}}$$

$$T_2 = 273 \cdot 7^{0.286} = 476 \text{ K}$$

Pri tem je  $x = c_p/c_v = 1.4$  eksponent adiabate za dvoatomske pline oziroma razmerje specifičnih toplot:

$$\frac{V_2}{V_1} = \left( \frac{p_1}{p_2} \right)^{1/x} = \left( \frac{1}{\varepsilon} \right)^{1/1.4}$$

$$V_2 = V_1 \left( \frac{1}{\varepsilon} \right)^{1/1.4}$$

$$V_2 = 1.0 \left( \frac{1}{7} \right)^{1/1.4} = 0.249 \text{ m}^3$$

Za izobarno kompresijo od stanja »2« v stanje »3« velja:

$$\frac{V_3}{T_3} = \frac{V_2}{T_2} \quad V_3 = \frac{V_2}{T_2} \cdot T_3$$

In ker je  $T_3 = T_1$ , sledi:

$$V_3 = \frac{T_1}{T_2} \cdot V_2 = \frac{273}{476} \cdot 0.249 = 0.143 \text{ m}^3$$

Za adiabatno ekspanzijo od stanja »3« v stanje »4« pa velja:

$$\frac{T_4}{T_3} = \left( \frac{p_4}{p_3} \right)^{(x-1)/x}$$

ker so  $T_3 = T_1$ ,  $p_3 = p_2$  in  $p_4 = p_1$ ; sledi:

According to agreement and result the led off is negative and by the energy balance it is in accordance with the principle of energy conservation. The work  $W_{12}$  can also be obtained as follows:

pri čemer je  $x$  eksponent adiabate in  $\varepsilon$  eksponent kompresije.

Sl. 2. Diagram p-V procesa prenosa energije s stisnjeniem zrakom.

Fig. 2. p-V diagram of the process of energy transmission by compressed air

$$\frac{V_2}{V_1} = \left( \frac{p_1}{p_2} \right)^{1/x} = \left( \frac{1}{\varepsilon} \right)^{1/1.4}$$

$$V_2 = V_1 \left( \frac{1}{\varepsilon} \right)^{1/1.4}$$

$$V_2 = 1.0 \left( \frac{1}{7} \right)^{1/1.4} = 0.249 \text{ m}^3$$

where  $x = c_p/c_v = 1.4$ , the adiabate power for two-atoms gases or the ratio of specific heats:

For the isobaric compression from state »2« to state »3« it applies:

$$\frac{V_3}{T_3} = \frac{V_2}{T_2} \quad V_3 = \frac{V_2}{T_2} \cdot T_3$$

and as  $T_3 = T_1$ , it follows:

For the adiabatic expansion from the state »3« into state »4«, however, it applies:

$$\frac{T_4}{T_3} = \left( \frac{p_4}{p_3} \right)^{(x-1)/x}$$

As  $T_3 = T_1$ ,  $p_3 = p_2$ , and  $p_4 = p_1$ , it follows:

ta visoka temperatura mora ostati konstantna pri razvodu zraka, tako da ob ekspanziji v delovnem stroju  $T_4 = T_1 \left( \frac{p_1}{p_2} \right)^{(x-1)/x} = 273 \left( \frac{1}{7} \right)^{0,286} = 156 \text{ K}$ , če je nekaj vloženo delo, ki ima učinkovitost celotne naprave. S tem tudi vse vloženo delo, ki je vloženo v delovni stroj, se na koncu ekspanzije vrne v prvotno stanje.

Praktično ni mogoče od začetka kompresije do konca ekspanzije vadrževati popolno izolacijo v delovnem stroju. S tem tudi vloženo delo, ki je vloženo v delovni stroj, se na koncu ekspanzije vrne v prvotno stanje.

$$\frac{V_4}{V_3} = \left( \frac{p_3}{p_4} \right)^{1/x}$$

$$V_4 = V_3 \left( \frac{p_2}{p_1} \right)^{1/x} = V_3 \cdot \varepsilon^{1/x}$$

1.2 Termodynamski prikaz dejavnosti naprave

$$V_4 = 0,143 \cdot 7^{1/1,4} = 0,574 \text{ m}^3$$

Z navedenimi podatki lahko opravimo energijske bilance preobrazb (energijske veličine zaokrožimo na dve mestni):

### 1. Kompresija

Po prvem glavnem zakonu termodinamike se ob kompresiji 1–2, ker je preobrazba adiabatna, delo spremeni v notranjo energijo. S tem je prostorninsko delo  $W_{12}$ :

$$W_{12} = \Delta U = m c_v (T_1 - T_2) \quad (9)$$

če je  $c_v = 720 \text{ J/kgK}$  specifična toplota zraka pri konstantni prostornini:

$$W_{12} = 1,29 \cdot 720 \cdot (273 - 476) = -1,9 \cdot 10^5 \text{ J}$$

Ob izobarni preobrazbi od stanja »2« v stanje »3« je dovedeno dodatno prostorninsko delo:

$$W_{23} = p_2 \cdot (V_3 - V_2) = 7,07 \cdot 10^5 \cdot (0,143 - 0,249) = -0,7 \cdot 10^5 \text{ J}$$

Obe deli sta »dovedeni« in s tem po dogovoru negativni [4].

Celotno vloženo prostorninsko delo pri preobrazbi 1–3 je:

$$W_{13} = W_{12} + W_{23} = (-1,9 - 0,7) \cdot 10^5 = -2,6 \cdot 10^5 \text{ J}$$

Ob stanju »3« ima zrak začetno temperaturo  $T_3 = T_1$ , kar smo dosegli tako, da smo ob izobarni preobrazbi odvedli toploto  $Q_{23}$ :

$$Q_{23} = m c_p (T_3 - T_2)$$

če je  $c_p = 1010 \text{ J/kgK}$  specifična toplota zraka pri izobarni preobrazbi,

$$Q_{23} = 1,29 \cdot 1010 \cdot (273 - 476) = -2,6 \cdot 10^5 \text{ J}$$

Using the cited data the energy balances of transformations can be done (the energy quantities are rounded up to two decimal places):

### 1. Compression

According to the first law of thermodynamics at the compression 1–2 the work is changed into internal energy, as the question is of an adiabatic change. Thus volumetric work  $W_{12}$  is:

If the specific heat of air at constant volume,  $c_v = 720 \text{ J/kg K}$  we have:

At the isobaric changes from state »2« to state »3« an additional volumetric work is supplied:

Both of the two works are »supplied«, and, as agreed, they are negative [4].

The total input volumetric work in transformation 1–3 is:

At state »3« the air temperature is its initial temperature  $T_3 = T_1$  attained by leading off the heat  $Q_{23}$  at isobaric transformation:

If the specific heat of air at isobaric transformation is  $c_p = 1010 \text{ J/kgK}$ , there is

Tudi odvedena toplota je po dogovoru in rezultatu negativna in po energijski bilanci v skladu z zakonom o ohranitvi energije.

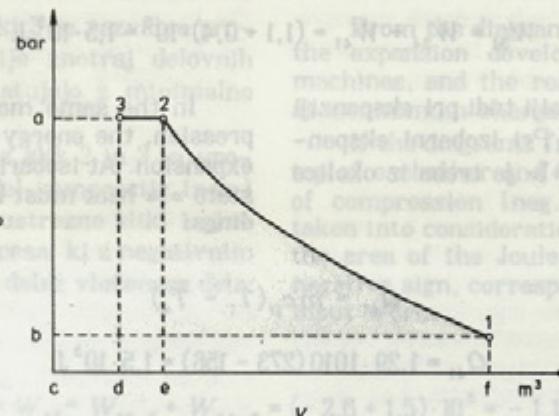
Delo  $W_{13}$  pa dobimo tudi takole:

$$W_{13} = x W_{12} = W_{12,t} \quad (11)$$

pri čemer je  $x$  eksponent adiabate,  $W_{12,t}$  pa tehnično delo kompresije:

$$W_{12,t} = 1,4 \cdot (-1,9) \cdot 10^5 = -2,6 \cdot 10^5 \text{ J.}$$

Slednje ponazarja slika 2, ki prikazuje celotni pretok dela pri kompresiji.



Sl. 2. Diagram p-V tehničnega dela komprimiranja zraka.  
Fig. 2. p-V diagram of the technical work of air compression

Ploščina lika 1–2–e–f–1 ustreza vloženemu delu (neg.)  $W_{12}$ , ploščina lika 2–3–d–e–2 je ekvivalentna vloženemu delu (neg.)  $W_{23}$ , ploščina lika 3–a–c–d–3 pomeni vloženo delo (neg.) za potiskanje zraka v rezervoar; zanj velja:

$$-p_3 \cdot V_3 = -7,07 \cdot 10^5 \cdot 0,143 = -1,0 \cdot 10^5 \text{ J.}$$

Ploščina lika 1–b–c–f–1 pa ob nasesavanju ustreza pridobljenemu delu (poz.) in je enako:

$$p_1 \cdot V_1 = 1,01 \cdot 10^5 \cdot 1,0 = 1,0 \cdot 10^5 \text{ J.}$$

Z upoštevanjem predznakov preostane senčena ploščina, ki ustreza tehničnemu delu  $W_{12,t}$ :

$$W_{12,t} = W_{12}(\text{neg.}) + W_{23}(\text{neg.}) + p_3 \cdot V_3(\text{neg.}) + p_1 \cdot V_1(\text{poz.})$$

According to agreement and result the led off heat is also negative and by the energy balance it is in accordance with the principle of energy conservation.

The work  $W_{13}$  can also be obtained as follows:

where  $x$  is the power of adiabate and  $W_{12,t}$  is the technical work of compression.

This is illustrated by Fig.2 showing the whole work development at compression.

The area of figure 1–2–e–f–1 corresponds to the input work (negative)  $W_{12}$ ; the area of figure 2–3–d–e–2 is equivalent to the input work  $W_{23}$  (negative); the area of figure 3–a–c–d–3 means the input work (negative) for feeding air into the reservoir; It is:

And the area of figure 1–b–c–f–1 represents the work obtained (positive) at suction, which is:

$$W_{12,t} = (-1,9 - 0,7 - 1,0 + 1,0) \cdot 10^5 = -2,6 \cdot 10^5 \text{ J.}$$

## 2. Ekspanzija

Pri adiabatni ekspanziji iz stanja »3« v stanje »4« pridobimo prostorninsko delo na račun notranje energije, torej:

## 2. Expansion

At the adiabatic expansion from state »3« to state »4« the volumetric work is obtained to the detriment of internal energy, thus:

$$W_{34} = \Delta U = mc_v(T_3 - T_4) \quad (12),$$

$$W_{34} = 1,29 \cdot 720 \cdot (273 - 156) = 1,1 \cdot 10^5 \text{ J}.$$

Ob izobarni preobrazbi od stanja »4« na stanje »1« pridobimo še prostorninsko delo:

At isobaric transformation from state »4« to state »1« the volumetric work is obtained:

$$W_{41} = p_4(V_1 - V_4) = 1,01 \cdot 10^5 \cdot (1,0 - 0,574) = 0,4 \cdot 10^5 \text{ J}.$$

S tem je celotno pridobljeno (pozitivno) prostorninsko delo:

By this the total volumetric work obtained (pos.) becomes

$$W_{31} = W_{34} + W_{41} = (1,1 + 0,4) \cdot 10^5 = 1,5 \cdot 10^5 \text{ J}.$$

### 1. Kompresija

Enako kakor pri kompresiji tudi pri ekspanziji opravimo energijsko bilanco. Pri izobarni ekspanziji od stanja »4« na stanje »1« je treba iz okolice dovesti toploto:

In the same manner as in the case of compression, the energy balance is also made for the expansion. At isobaric expansion from state »4« to state »1« heat must be supplied from the surroundings:

$$Q_{41} = mc_p(T_1 - T_4) \quad (13),$$

$$Q_{41} = 1,29 \cdot 1010 (273 - 156) = 1,5 \cdot 10^5 \text{ J}.$$

Celotno ekspanzijsko delo je podobno kakor pri kompresiji enako tehničnemu delu:

Similarly as at compression, the total expansion work is equal to the technical work:

$$W_{31} = xW_{34} = W_{34,t} \quad (14),$$

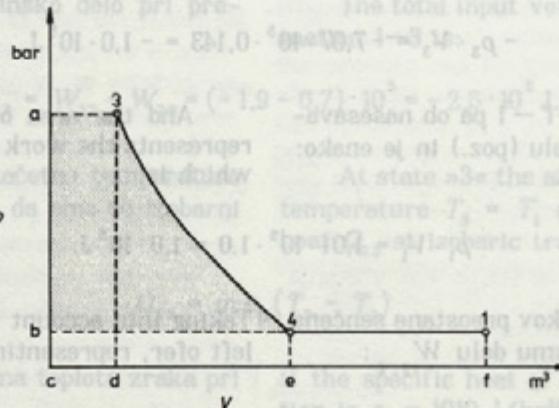
$$W_{34,t} = 1,4 \cdot 1,1 \cdot 10^5 = 1,5 \cdot 10^5 \text{ J}.$$

**Podobni diagram pa prikazuje slika 3.**

A similar diagram is shown in Fig. 3.

Celotno vloženo prostorninsko delo pri preobrazbi 3–3–1 je:

The total input volumetric work in transform-



Sl. 3. Diagram p-V tehničnega dela ekspanzije zraka.

Fig. 3. p-V diagram of the technical work of air expansion

Tedaj Ploščina lika 3 – 4 – e – d – 3 ustreza pridobljenemu prostorninskemu delu  $W_{34}$  (poz.). Ploščina lika 3 – d – c – a – 3 ustreza pridobljenemu polnilnemu delu  $p_3 V_3 = 1,0 \cdot 10^5$  J (poz.). Ploščina lika 4 – 1 – f – e – 4 ponazarja pridobljeno prostorninsko delo pri izobarni ekspanziji  $p_4(V_1 - V_4)$  (poz.). Ploščina lika 1 – f – c – b – 1 ustreza izpušnemu delu  $p_1 V_1 = 1,0 \cdot 10^5$  J (neg.).

Senčeni del diagrama je torej ekvivalenten tehničnemu ekspanzijskemu delu:

$$W_{34,t} = W_{34}(\text{poz.}) + p_3 V_3(\text{poz.}) + p_4(V_1 - V_4)(\text{poz.}) + p_1 V_1(\text{neg.}),$$

$$W_{34,t} = (1,1 + 1,0 + 0,4 - 1,0) \cdot 10^5 = +1,5 \cdot 10^5 \text{ J.}$$

Iz poteka diagrama na sliki 3 je razvidna problematičnost poteka ekspanzije znotraj delovnih strojev in zakaj le-ti ne obratujejo z minimalno polnitvijo.

Če prekrivamo diagrama s slik 2 in 3 in upoštevamo predznak tehničnih del kompresije (neg.) ter ekspanzije (poz.), dobimo ustrezeno sliku 1 ploščino Jouleovega krožnega procesa, ki z negativnim predznakom pomeni izgubljeni delež vloženega dela:

$$W_0 = \sum W_{IJ} = W_{12,t} + W_{34,t} = (-2,6 + 1,5) \cdot 10^5 = -1,1 \cdot 10^5 \text{ J.}$$

Ustrezeno našemu namenu definiramo termodynamični Izkoristek kot razmerje med pridobljenim in vloženim delom:

$$\eta_{th} = \frac{W_{34,t}}{|W_{12,t}|} = \frac{1,5 \cdot 10^5}{2,6 \cdot 10^5} = 0,58 \approx 0,6 \quad (15).$$

## 2. GOSPODARNOSTNE IZBOLJŠAVE

Celotni Izkoristek instalacije za prenos energije s stisnjениm zrakom z upoštevanjem posameznih izkoristkov iz enačb (2), (5), (8) in (15) bi torej bil:

$$\eta = \eta_k \eta_c \eta_d \eta_{th}$$

$$\eta = (0,8 - 0,9)(0,5 - 0,7)(0,5 - 0,7)0,6 \approx (0,1 - 0,3)$$

Kakor je navedeno v (1).

The area of figure 3 – 4 – e – d – 3 corresponds to the obtained volumetric work  $W_{34}$  (pos.). The area of figure 3 – d – c – a – 3 corresponds to the work obtained at charging  $p_3, V_3 = 1,0 \cdot 10^5$  J (pos.). The area of figure 4 – 1 – f – e – 4 represents the volumetric work obtained at Isobaric expansion  $p_4 (V_1 - V_4)$  (pos.). The area 1 – f – c – b – 1 corresponds to the accomplished work  $p_1, V_1 = 1,0 \cdot 10^5$  J (neg.). Thus, the hatched part of the diagram is equivalent to the technical expansion work:

From the diagram in fig. 3 the doubtfulness of the expansion development inside the working machines, and the reason why they don't operate at a minimum charge can be seen.

If the diagrams from Figs. 2 and 3 are laid on top of each other and the signs of technical works of compression (neg.) and expansion (pos.) are taken into consideration, in accordance with Fig. 1, the area of the Joule cycle is obtained, which a negative sign, corresponds to the lost share of the input work:

In conformity to our purpose the thermodynamic efficiency is defined as the ratio of the obtained to input works:

## 2. ECONOMY IMPROVEMENTS

Consequently, taking into account the particular efficiencies from equations (2), (5), (8) and (15) the total efficiency of the energy transmission, installation would be:

Increasing of total installation efficiency over 0.3 is not feasible for compressed air supply.  
as cited in (1).  
(1) v mešavini slavnični jenuz

Iz slednjega je popolnoma razumljivo in upravičeno vsakršno prizadevanje za zvečanje vrednosti posameznih izkoristkov. Vendar pa se je treba zavedati, da vsako zvečanje vrednosti terja določeno naložbo sredstev, npr. za boljše materiale posameznih strojnih elementov, močnejše dimenzionaliranje in tudi dodatne elemente. V vsakem primeru pa je treba dosegel najugodnejše razmerje.

— Na prvem mestu navedimo izboljšave, ki imajo učinek na termodynamični izkoristek in so bile na tem področju že zelo zgodaj izčrpane gospodarske in upravičene možnosti.

V fazi kompresije je z izdatnim hlajenjem kompresijskih prostorov (npr. dvojno oplaščenih valjev, okrovov ventilov) dosegena politropna preobrazba z eksponentom  $n = 1.3$ . Uvedena je stopenjska kompresija, tako da se med dvema stopnjama zrak v vmesnem hladilniku ohladi na začetno temperaturo. Ker vsaka stopnja terja dodatne naprave, kakor na primer valj pri batnem kompresorju in vmesni hladilnik, je za razmere v rudniku iz ekonomskih razlogov primerna dvostopenjska kompresija. Po znani formulji za določitev politropnega dela komprimiranja v stopnjah:

$$W_{12, \text{pol}} = z \frac{n}{n-1} p_1 V_1 \left( \epsilon^{(n-1)/zn} - 1 \right) \quad (16),$$

kjer je z število stopenj, ugotovimo za naš primer vrednost kompresijskega dela za  $n = 1.3$  in  $z = 2$ :

$$W_{12, \text{pol}} = 2 \frac{1.3}{1.3-1} 1.01 \cdot 10^5 \cdot 1.0 \left( 7^{\frac{(1.3-1)}{(2 \cdot 1.3)}} - 1 \right) = 2.2 \cdot 10^5 \text{ J.}$$

Pri delovanju delovnih strojev ne moremo pričakovati nikakršnih termodynamičnih izboljšav, zato je že ob analizi ugotovljeno delo skrajna zgornja meja.

Po definiciji (15) ugotovimo novo vrednost:

$$\eta_{\text{th, maks}} = \frac{W_{34, t}}{W_{12, \text{pol}}} = \frac{1.5 \cdot 10^5}{2.2 \cdot 10^5} = 0.68 \approx 0.7 \quad (17).$$

Dobljena vrednost pomeni največji gospodarsko upravičeni dosežek. Lahko ugotovimo, da dobljena največja vrednost termodynamičnega izkoristka ne vpliva na celotni izkoristek, da bi bil zunaj intervala podanem v (1).

From the above statements it can be seen that any effort to increase the values of particular efficiencies are quite understandable and justified. It should be realized, however, that each increase of values requires a certain investment of means, e.g. for better materials for machine parts, greater dimensions, and also for additional elements. In any case the optimum proportion should be attained.

— The improvements having some influence on the thermodynamic efficiency, and those for which the economical and justified possibilities in this domain have already been exhausted, will be mentioned in the first instance.

In the phase of compression a polytropic transformation with the power of  $n = 1.3$  is attained by abundant cooling of the compression compartments (e.g. double-shelled cylinders of valve cases). A gradual compression is introduced such that between two stages the air is cooled down to the initial temperature in an intermediate cooler. As additional equipment, such as, a cylinder for a reciprocating compressor and an intermediate cooler is required for each stage, a two-stage compression is suitable for mine conditions for economical reasons. According to the known formula for determining the polytropic compression work in stages:

where  $z$  is the number of stages, the value of compression work for  $n = 1.3$  and  $z = 2$  is found for our case as:

In working engine operation no thermodynamic improvements can be expected, therefore the work already found by analysis is the utmost upper limit.

According to definition (15) the new value is found as

The value obtained means the highest economically justified achievement. It can be stated that the obtained maximum value of thermodynamic efficiency doesn't influence the total efficiency in such a way that it would be outside of the interval given in (1).

Analizirajmo še možnosti izboljšav drugih izkoristkov.

— Izkoristek kompresorja (2) je odvisen izključno od strojniško konstrukcijskih izvedb sklopov, ventilov in priključkov. Ker so že uporabljene gospodarnostno še upravičene rešitve, ni realno pričakovati kakršnekoli pomembne izboljšave.

— Izkoristek delovnih strojev (6), (7) in (8) tudi po analizi praktično ne more imeti pomembne večje vrednosti; zveča se lahko kvečjemu na spodnji meji intervala.

— Izkoristki razvoda (3), (4) in (5) so sestavljeni iz bistveno različnih dejavnikov. Del, ki upošteva znižanje tlaka (4), je odvisen od dimenzioniranja prerezov cevovoda in razdalj do uporabnikov. Za dimenzioniranje prerezov je določena gospodarnostna meja. V odvisnosti od oddaljenosti delovišč so padci tlakovlahko tudi majhni, če razdalje niso velike, če pa upoštevamo dejanske razdalje v rudnikih in ustrezeni postopek optimiziranja prerezov cevovoda, kakor se običajno dela, je podatek po (4) praktično optimalen in ukrepi za izboljšanje ne bi bili upravičeni.

Drugi dejavnik, ki upošteva izgube zraka zaradi netesnosti (3), vzbuja več upanja. Dolgo je že uveljavljen ukrep, da morajo biti deli cevovoda zvarjeni, vendar še vedno obstajajo v bližini delovišč in na njih začasno montirani odseki, kjer so netesnosti neizbežne. Prav tako se ni mogoče izogniti izgubam na armaturah in predvsem na priključkih. Računalniško vodenje bi moglo poseči prav na to področje, in sicer tako, da bi z avtomatskim zapiranjem ventilov izključevali posamezne razvodne veje, kjer trenutno ni porabe zraka in s tem izključili izgubo zaradi netesnosti v teh vejah.

Taka rešitev je mogoča samo pri močno razvejanih sistemih in pri selektivni organizaciji dela. Predvsem pa ima veliko večji vpliv na dimenzioniranje potrebne zmogljivosti kompresorske postaje kakor pa na izboljšanje izkoristka za vloženo delo pri komprimiraju. Vsekakor pa je tak postopek popolnoma konkreten, zato je treba v vsakem praktičnem primeru s temeljito analizo vseh vplivnih dejavnikov ugotoviti, ali se ukrep izplača ali ne. Težko je pričakovati, da bi vse navedeno moglo izboljšati izkoristek razvoda (5) nad zgorajno mejo intervala.

Poprejšnja analiza nas lahko prepriča, da pri znani tehnologiji ni uresničljivo zvečanje izkoristka celotne instalacije za daljinsko energijsko oskrbo s stisnjениm zrakom nad 0,3.

Let us still analyse the improvement possibilities for other efficiencies.

— The compressor efficiency (2) depends exclusively on the machine-constructional execution of aggregates, valves and attachments. As the economically justified solutions have already been used, any significant improvement can't really be expected.

— The working machine efficiency (6), (7), and (8), according to the analysis can't have any important higher value either; they can be increased at the lower interval limit at the most.

— The distribution efficiencies (3), (4) and (5) are composed of essentially different factors. The part taking into account the pressure drop (4) depends on the pipeline cross-section dimensions and distances to the consumers. An economy limit is fixed for cross-section dimensioning.

Dependent on the distance from the faces, the pressure drops may also be small, if the distances aren't long, but if the actual distances in mines and the corresponding dimensioning method for pipeline cross-section are taken into account, the data according to (4) is practically optimum and improvement measures wouldn't be justifiable.

The second factor, taking into account air losses due to leakages, (3) raises more expectations. For a long time the measure has been in force that pipeline parts should be welded, nevertheless sections exist near the faces of work and on them in which leakages are unavoidable. Likewise, it is impossible to avoid losses at fittings and attachments. Computer control could help in this very domain, namely in such a way, that particular distribution branches in which there is no air consumption at the moment, would be disengaged by automatically shutting off the valves and thus eliminating the leakage loss in these branches.

Such a solution is only possible in highly ramified systems and in selective work organization. But primarily, its influence on the dimensioning of the required compressor plant capacity is much greater than that on the efficiency improvement for the input compression work. Such a procedure, however, is quite concrete at any rate, and for this reason, in each practical case it is necessary to find out whether a measure is worth the trouble or not. It can hardly be expected that all the cited facts could improve the distribution efficiency over the upper interval limit.

The analysis already mentioned shows that at the known technology the increasing of total installation efficiency over 0.3 is not feasible for the remote compressed air supply.

### 3. SKLEP

V sestavku smo izbrali Jouleov krožni proces za model celotnega termodinamičnega dogajanja pri prenosu energije s komprimiranim zrakom. Model omogoča elementarno in nadrobno analizo vseh faz dela z ustreznimi preobrazbami in na koncu dovoljuje tudi kakovostno in količinstveno oceno termodinamičnega izkoristka v proces vloženega dela.

V zadnjem poglavju so glede na poprejšnjo analizo ocenjene vrednosti odločilnih dejavnikov v celotnem izkoristku, predvsem glede na možnost izboljšav. Ugotovitev dovoljuje sklep, da ni uresničljivo zvečanje celotnega izkoristka v proces vloženega dela nad mejo  $\eta = 0,3$ .

### 3. CONCLUSION

In the paper the Joule cycle was chosen as the model of all the thermodynamic events in energy transmission by the compressed air. The model makes the elementary and detailed analysis of all work phases with corresponding transformations possible. Finally, it also permits the quality and quantity estimations of the thermodynamic efficiency of work put into the process.

With regard to the analysis already mentioned the values of decisive factors in the total efficiency are estimated in the last chapter, above all in view of the improvements possible. From the findings the conclusion may be drawn that total efficiency increase over the limit of  $\eta = 0,3$  of work put into the process is not attainable.

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Naslov avtorjev:

prof. dr. Franc Vidergar, dipl. inž.  
prof. dr. Franc Runovc, dipl. inž.  
oba

Fakulteta za naravoslovje in tehnologijo  
Univerze v Ljubljani  
Odsek za rudarstvo

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Address of the authors:

Franc Vidergar, D. Sc., professor, dipl. ming. eng.  
Franc Runovc, D. Sc., professor, dipl. eng.  
both of them

Faculty of Sciences and Technology,

University in Ljubljana,

Mining Department

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The value obtained is statistically justified. It can be stated that the obtained maximum value of thermodynamic efficiency doesn't influence the total efficiency in such a way that it would be outside of the interval given in (1).

Dobijena vrednost pomenja največji gospodarsko upravičeni doseg. Lahko ugotovimo, da dobijena največja vrednost termodinamičnega izkoristka ne vpliva na celotni izkoristek, da bi bil zunaj intervala podanem v (1).