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Vrednost in obračunavanje energije v plinovodnem sistemu

Energy Value and its Settlement in a Gas Transmission System

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Članek povzema nekatere zaznave, ki so poznane v sistemski teoriji in inženirski termodynamiki in so vezane na pojma krajevne in časovne skale. Te zaznave omogočajo svojstven prijem pri konstruiranju, nadzoru in upravljanju procesnih sistemov. Elementi visokotlačnega plinovodnega sistema, izbranega kot primer, so bili konstruirani v skladu z določenimi referenčnimi skalami tako, da se je bilo mogoče izogniti zamrznjenim spremenljivkam. Eksergetska optimizacija transmisije plina je bila izvedena na podlagi simuliranja procesov, ki se odvijajo simultano na različnih časovnih skalah.

The paper summarizes some of the percepts known in system theory and in engineering thermodynamics, in terms of time and space scales, which enable unique access to complex systems design, control and management. Elements of a high pressure gas transmission system, which was taken as an example, were structured according to a particular reference scale so that the appearance of frozen variables could be avoided. Exergetic optimization of gas transmission was based on process simulations running simultaneously on different time scales.

0 UVOD

0 INTRODUCTION

Odločitve, ki jih morajo opraviti raziskovalci, konstrukterji in upravljalci postajajo s tehnološkim razvojem vse bolj kompleksne in težko razumljive. Tradicionalni načini velikokrat kažejo omejitve, posebno v primerih, ki združujejo različna prizadevanja. Raziskovalci sistemov morajo, dodatno k »funkcionalno naravnanim« sistemom, obvladovati podatkovne baze in sisteme, ki se odzivajo v realnem času [1]. Na srečo se je v zadnjih desetletjih razvila sistemská znanost kot panoga, ki obeta uspešno obravnavo takšnih kompleksnih sistemov [2].

Kompleksni sistem je v bistvu večplastni sistem z več prostostnimi stopnjami. Obravnavana na enem samem nivoju zahteva hkratni matematični postopek z velikim številom spremenljivk. Če je razgrajevanje sistema v več podsistemov izvedljivo, nas takšna pot vodi v boljše spoznavanje in razumevanje okolice sistema. Pri tem velja poudariti, da razgrajevanje sistema ni poljubno, ker moramo običajno slediti načelom različnih znanstvenih panog. To pogosto vodi k stroškom [3]. Termoekonomika se je pojavila kot rezultat potreb po konstruiranju optimalnih kompleksnih sistemov. Nekaj novih korenin je tej panogi predložil Rant [4], oče pojma eksjergetika, ki je bila prvič omenjena v članku z naslovom: »Vrednost in obračunavanje energije«. Prof. Rantu je namenjen ta prispevek s podobnim naslovom ob 90. obletnici njegovega rojstva.

With technological advance the decisions that must be made by researchers, designers and managers become more and more complex and hence more difficult to understand. Traditional approaches have their limitations, particularly when dealing with issues that span many fields of endeavor. In addition to »function-oriented« systems, systems developers have also to cope with issues of database systems and real-time systems [1]. Fortunately, a systems science has emerged in the past few decades as a discipline which shows promise of being able to deal with such complexity successfully [2].

A complex system is essentially regarded as a multizone, multidegree-of-freedom system and its treatment as one zone involves the mathematical treatment of a large number of variables at one time. If a decomposition of the system into subsystems can be devised, a closer understanding of a system environment can be provided. The decomposition of the system must follow the principles of various scientific disciplines, which makes the decomposition not totally arbitrary. This very often leads to capital expenditures [3]. Thermoconomics has emerged as a result of such a need for the optimal design of complex systems. Some of the first steps in this discipline were proposed by Rant [4] who is the father of the exergy term which was mentioned for the first time under the title: »Energy value and its accounting«. This article, under similar title, pays tribute to Prof. Rant on the occasion of his 90th birthday anniversary.

Članek povzema nekatere zaznave, povezane s pojmom krajevne in časovne skale, ki so poznane v sistemski teoriji in inženirski termodynamiki. Sistem obravnava izključno v odvisnosti od časa v obliki, opisani v [7], za razliko od filozofije Tribusa [5] in Ranta [6], ki sta večinoma obravnavala kompleksne sisteme statično. Članek ni namenjen prikazovanju nadzora in upravljanja sistema transmisije plina v podrobnosti, ki je izbran le kot primer. Namenski članka je prikazati eksergetski zapis, ki ga lahko uporabimo na področju sistemskega razmišljanja.

Visokotlačna plinovodna mreža v Sloveniji je sestavljena iz 270 km dolgega glavnega voda in okoli 450 km razdeljevalnih vej. Plin različne kakovosti in dinamike je dobavljen na obeh krakih glavnega voda in mora zadostiti zahtevam porabnikov po masnem pretoku in tlaku. Sistem je določen z razmeroma preprosto prenosno funkcijo samega sistema in zapletenim delovanjem okolice na različnih časovnih skalah. Avtor verjame, da bo ta aplikacija, ki v praksi že poteka [8], prispevala k boljšemu razumevanju optimizacije sistemov na več skalah.

1 ZAZNAVE

1. *Sistem.* Sistem P je obravnavan kot skupen elementov, ki so povezani v organizirano celoto [2]. Vsak podsistem poenotnih internih lastnosti se imenuje element. Velikost takšnih elementov je odvisna od opazovalčeve časovne skale τ_Q in krajevne skale Δ_Q . Opazovalec (človek) Q se mora vedno sprijazniti z množico reduciranih makroskopskih spremenljivk zaradi navidezne homogenosti elementov [3]¹.

V splošnem je sistem definiran samo s tistimi elementi, ki so v medsebojnem stiku. Povezanost med elementoma A in B obstaja takrat, ko je obnašanje enega elementa odvisno od obnašanja drugega elementa [1]. Povezave med elementi sistema popisujemo s tokovi podatkov, npr. tok snovi, energij ali informacij. Koncentracija in narava povezav med elementi omogočata razlikovati *sistem* (s koncentriranimi povratnimi zvezami) od pripadajoče *okolice* (vhodno-izhodne povezave s sistemom). Ločnica med sistemom in njegovo okolico je definirana z mejo sistema. Absolutno razločevanje je teoretično mogoče pri konstrukciji *izključenega sistema*. Nasprotno, odprt sistem izmenjuje prek meje s svojo okolico snov, energijo in informacijo [1].

Značilna lastnost, pripisana elementu ali procesu, se imenuje atribut. Glavno skrb namenjamo spremembam atributov elementov in procesov, ki nas zanimajo. [1]. Nekateri atributi elementov sistemov so poznani kot spremenljivke stanja

The paper summarizes some of the percepts known in system theory and in engineering thermodynamics, in terms of time and space scales. In distinction to the philosophy of Tribus [5] and Rant [6] who have envisaged complex systems most of the time as static, the paper deals with the system as strictly time-dependent in terms as described by Woods [7]. It is not the intention here to give an example of how complex gas transmission system control and management has been solved in detail, but rather to point out how useful exergetic description can be in the area of systems thinking.

The high pressure gas transmission network in Slovenia consists of a 270 km long mainline and about 450 km of distribution lines. Gas of different quality and dynamics is supplied at both ends of the mainline and must meet consumer requirements on mass flow rates and pressures. The system is defined by a fairly simple transfer function, and complicated/complex environmental effects which appear on different time scales. It is believed that this application, which runs in a real field [8], will contribute to the better understanding of multiscale systems optimization.

1 PERCEPTS

1. *System.* A system P is considered as an assembly of elements related in an organized whole [2]. Any sub-system having uniform internal properties is termed an element. The size of these elements depends upon the observer's time τ_Q and length scales Δ_Q . An element appears uniform to a given (human) observer Q, who must always be content with a greatly reduced set of macroscopic variables [3]¹.

A system is generally only defined by those elements which are in contact with each other. A relationship can be said to exist between system elements A and B if the behavior of either is influenced by other [1]. Relationships between system elements are described by data flows, such as the flow of materials, energy, or information. The concentration and nature of relationships between elements helps us to distinguish a *system* (with concentrated feedback relationships) from its environment (input-output relationships with the system). The demarcation between a system and its *environment* is made explicitly by defining the boundary of the system. The distinction is absolute in the theoretical construct of a *closed system*. Conversely, an open system exchanges material, energy and information with its environment across a boundary [1].

A characteristic property ascribed to an element or process is termed an attribute. It is the changes in the elemental and processual attributes of interest that are of prime concern [1]. Some elemental attributes of systems are known as state variables of the system and thus the system can be described by a state vector.

sistema, ki omogočajo popis sistema z vektorjem stanj. Časovne spremembe stanj sistema sestavljajo trajektorijo stanj (pot preobrazbe). Celoto, v kateri se lahko pojavijo (gibljejo) trajektorije, imenujemo prostor stanj sistema. Če se časovna stanja sistema enolično preslikajo iz enega v drugo, imenujemo sistem determinističen. V kompleksnejših sistemih se stanja lahko preslikajo iz enega v več mogočih stanj ali nasprotno, kar je lastnost nedoločenih ali verjetnostnih sistemov.

V kompleksnejših sistemih se pogosto pojavijo koherentne strukture z ustrezeno komunikacijo in nadzorom, ki sestavljajo podsisteme elementov z značilnim delovanjem celic, zmožnih »življenja«. To jasno prinaša nekaj »dodatnega« h *kakovosti storitve sistema*.

2. *Inženirski sistem.* Inženirski sistem je obravnavan kot bitnost, zgrajena v splošnem iz številnih elementov, ki jih je naredil človek in so med seboj v nekem stiku, tako da lahko vplivajo drug na drugega. Pogosto so oblikovane koherentne strukture elementov z ustreznim nadzorom z namenom, da bi povečali kakovost storitve sistema².

Sistem P zajema v splošnem dve podmnožici elementov. Prva podmnožica obsega samo tiste elemente, ki jih Q lahko nadzira in se zato imenuje *nadzorovani sistem CP*. Druga podmnožica zajema preostale elemente, tj. tiste elemente, ki vplivajo na CP, ki pa jih Q ne more nadzirati. Ta podmnožica se imenuje *okolica EP*. Q običajno želi imeti čim več elementov pod nadzorom, da bi povečal kakovost storitve sistema. Izkaže se, da elementi EP ne morejo biti v celoti pod nadzorom, lahko pa so nekateri med njimi v omejenem obsegu izpostavljeni vplivu Q³. Zato je zelo uporabno ločevati elemente širše okolice, ki ne morejo biti pod vplivom Q, od tistih, ki so lahko pod posrednim vplivom in imajo sposobnost pomembno spremeniti karakteristike ožje oziroma lokalne okolice.

3. *Termodinamski sistem.* Sistem (P, Q) imenujemo termodinamski sistem, če so $\{x_r\}$, $m \leq r \leq m + n$ njegove termodinamske spremenljivke. Glavni namen klasične termodinamike je osnovati razmerja, ki vključujejo te spremenljivke in njihove izpeljanke. Podmnožica teh spremenljivk, ki jo sestavljajo termodinamske koordinate, je namenjena za opredelitev prostora stanj, preostale spremenljivke pa so potem funkcije tega stanja [3].

Naj bo z $X_1 \rightarrow X_2$ označen proces spremenjanja elementa množice CP od stanja X_1 do stanja X_2 . Če je $\tau_{PI} \sim \tau_Q$ za vse t v časovnem intervalu (t_1, t_2) , potem se $X_1 \rightarrow X_2$ imenuje *ravnotežni proces*. Trajektorija stanj je zvezna. Če je $\tau_{PI} \ll \tau_Q$ v trenutku t v intervalu (t_1, t_2) , potem se $X_1 \rightarrow X_2$ imenuje *neravnotežni proces*.

The change in system states over time forms the state trajectory. The totality in which the trajectory may appear (move) is termed the state space of the system. If the state variables of the system map on a one-to-one basis with their future states, the system is called deterministic. In more complex systems, the system state variables may map on a many-to-one or one-to-many basis, and the system is then called indeterminate or probabilistic.

In complex systems, it very often happens that coherent structures with appropriate communication and control are formed as subsets which act as viable units. This clearly brings something additional to the *quality of system performance*.

2. *Engineering system.* An engineering system is considered to be an entity composed generally of a number of man-made elements which are in some form of contact with each other, so that interactions are possible between them. To increase the quality of a system's performance, very often coherent structures are formed with appropriate control².

In general, a system P consists of two subsets. The first subset considers only those elements Q is able to control and is therefore called *controlled system CP*. The second subset consists of what is left over, i.e. of all those elements which act on CP elements, but cannot be controlled by Q. This subset is called *environment EP*. To increase the quality of a system performance, Q needs to have as many elements under control as possible. As a result, even though EP elements cannot be entirely controlled, some of them can, to a limited extend, be exposed to the influence of Q³. It is therefore very useful to distinguish the elements of the *wider environment*, which cannot be affected by Q at all, from those which can be indirectly affected and can significantly change the characteristics of the *narrower or local environment*.

3. *Thermodynamic system.* The system (P, Q) is called thermodynamic system if $\{x_r\}$, $m \leq r \leq m + n$ are its thermodynamic variables. The principal aim of classical thermodynamics is to establish relationships involving these variables and their derivatives. A subset of these variables, termed the thermodynamic coordinates, serves to define a state-space, and the remaining variables are then functions of state [3].

Let us denote the change of any CP element from the state X_1 to the state X_2 by a process $X_1 \rightarrow X_2$. If $\tau_{PI} \sim \tau_Q$ for all t within the time interval (t_1, t_2) , then $X_1 \rightarrow X_2$ is termed the *equilibrium process*. The state trajectory is continuous. If $\tau_{PI} \ll \tau_Q$ at instant t within (t_1, t_2) , then $X_1 \rightarrow X_2$ is termed the *non-equilibrium process*.

Spremenljivke stanja se kažejo kot sproščene in procesa ni mogoče nadzorovati. Če je $\tau_{PI} \gg \tau_Q$ za vse t v intervalu (t_1, t_2) , potem Q zapaža statično sliko P, ki kaže, da nadzor ni potreben. Spremenljivke stanja se kažejo v zamrznjeni obliki. Če Q želi zmanjšati τ , potem morajo biti spremenljivke, ki so se prej pojavljale v sproščeni obliki, dodane k listi termodinamskih koordinat in nekatere spremenljivke na drugem koncu časovne skale lahko obravnavamo kot zamrznjene [3]⁴.

Proces $X_1^* \rightarrow X_2^*$, pri katerem se izolirani sistem CP + EP razvije od stanja X_1^* do stanja X_2^* v končnem časovnem intervalu, se imenuje *povračljiv*, če je nasprotni proces $X_2^* \rightarrow X_1^*$ mogoč in *nepovračljiv*, če nasprotni proces ni mogoč. Proses $X_1^* \rightarrow X_2^*$ je vedno nepovračljiv, če dinamika na skali, manjši od τ_Q , ni upštevana⁵. Od tod izhaja, da delitev elementov lahko pomeni pot k učinkovitejšemu sistemu. Če definiramo eksergijo kot mero mogoče (ali razpoložljive pri danih CP in EP strukturah) kakovosti storitve sistema, potem je celo na eni sami skali τ mogoče pridobiti več s strukturiranjem elementov v sklope zmožne »življenja«⁶.

2 PLINOVODNI SISTEM (GTS)

To delo izhaja iz študije delovanja in upravljanja slovenske visokotlačne transmisijske mreže za zemeljski plin, kjer so elementi nadzora geografsko razpršeni [9]. V načelu imamo lahko cevovodni sistem za mrežo povezanih komponent, h katerim sodijo kraki, vozlišča, oprema, zunanjí krmilniki itn. Definicija sistema se nanaša na topologijo GTS, ki jo omejuje izbor opazovalčevih skal τ_Q in Δ_Q . Na »ničelnem nivoju« ni mogoče prilaganje (optimizacija) lokalnemu energetskemu trgu. V primeru dobave plina se pri nestacionarnih pretokih energetski trg kaže kot širša okolica. Pri prevelikih odjemih plina je edino mogoče upravljanje splošna redukcija dobave porabnikom. Pri nadalnjem razgrajevanju lahko ločimo porabnike po njihovih potrebah. Dobava plina v GTS se lahko loči na plin iz skladišča in na kapacitete zunanjih transportnih poti [9]. Večja ko je dinamika »motenj« v tlaku plina in pretoku, težavnejši je nadzor mrežnega sistema. Po naših izkušnjah je koristno razločiti sistem kot sestavljenko nadzorovanih elementov CP in deloma nadzorovanih (s predvidljivim obnašanjem) elementov EP, razvrščenimi v koherentne strukture zmožnih »življenja« na različnih časovnih skalah. V naših študijah smo označili konstrukcijo s tremi podsistemi [8]. Povezani so lahko s časovnimi okni, definiranimi s pomembnimi neravnotežnimi učinki. Vsak podistem je opisan z ustreznim matematičnim sistemom, ki zadovoljuje funkcjske zahteve sistema.

The state variables appear relaxed and the process is out of control. If $\tau_{PI} \gg \tau_Q$ for all t within (t_1, t_2) , Q observes the static picture of P, and there seems nothing to be controlled. The state variables appear frozen. If Q wishes to reduce τ , variables previously in relaxed equilibrium must be added to the list of thermodynamic coordinates, and some variables from the other end of the time scale may be assumed frozen [3]⁴.

A process $X_1^* \rightarrow X_2^*$ in which an isolated system CP + EP evolves from state X_1^* to state X_2^* in a finite time is *reversible* if the process $X_2^* \rightarrow X_1^*$ is possible, and *irreversible* if it is not. A process $X_1^* \rightarrow X_2^*$ is always irreversible when the dynamics on a smaller scale than τ_Q is ignored⁵. Hence, partitioning of elements may lead towards a more effective system. If we define exergy as a measure of the possible (or available at given CP and EP structures) quality of system performance, then even at the same scale τ one may gain more when structuring of elements into viable units is possible⁶.

2 GAS TRANSMISSION SYSTEM (GTS)

This work arises from a study of the operation and control of the Slovenian high pressure gas transmission network, in which the controllable elements are geographically dispersed [9]. In principle, a pipeline system can be considered as a network of interconnecting components, including legs, nodes, equipment, external regulators etc. System definition is related to the GTS topology constrained by τ_Q and Δ_Q as seen by the observer. At »zero level«, no adaptation (optimization) to the local energy market demand is possible. In the case of non-steady gas flow rates, the energy market appears as the wider environment. At too high gas off-takes, the only possible management is overall gas supply reduction. At further decomposition, customers may be distinguished according to their needs, while the gas supply may be partitioned into the gas storage and external gas flow rate capacities [9]. The greater the variety of »disturbances« in gas pressure and gas flow rates, the more difficult becomes the control of the network system. In our experience, it is useful to distinguish the system as a composition of controllable elements CP and partly controllable (or predictable) elements EP, which could be assorted into viable units according to different time scales. Three subsystems were distinguished in our studies based on such a construction [8]. They could be linked by time windows defined by significant non-equilibrium events. Each subsystem process runs on an unique mathematical system to meet the system functional requirements.

Podsistem nadzora plina (GCS) je določen z najmanjšo časovno skalo, potrebno za posnemanje vseh merjenih veličin (npr. tlak, pretok, temperaturo itn). GCS neposredno veže elemente sistema, npr. merno regulacijske postaje, in omogoča opazovalcu spremnijati tlake in pretoke. Podsistem modeliranja toka plina (GMoS) uporablja standardne transportne enačbe za simuliranje ustaljenega in prehodnega toka plina v realnem času. Rezultati numeričnega simuliranja so sprotno primerjani z izmerjenimi količinami. Pri znanih (napovedanih ali predvidenih) dobavah plina omogoča tudi napovedovanje tlaka in količine plina v plinovodu. Razlika količin plina v plinovodu med največjim in najmanjšim tlačnim profilom se imenuje notranja kapaciteta plinovoda. Zaradi neusklajenosti dinamike v dotoku in odjemu plina se notranja kapaciteta plinovoda s časom spreminja. Upravljanje plina (GMS) zadeva podatke v daljši prihodnosti. Tu se uporablajo metode napovedi, ki zmanjšujejo količino podatkov ob ohranjanju bistvenih informacij [5]. Čeprav lahko GMS deluje kot samostojni sistem, je njegovo optimalno vlogo v določanju vpliva ožje okolice na notranjo kapaciteto plinovoda mogoče doseči z integracijo napovedi obremenitve in dobave plina (metode verjetnosti) z induktivnim odločanjem. To dosežemo z izborom ustreznih časovnih skal in uporabo koncepta mehanske eksjergetike plina. Problem sklenitve takšnega sistema je bil rešen z ustreznou povezavo prek časovnih oken. Razviti so bili inteligentni stiki, ki takšno povezavo omogočajo⁷.

3 EKSERGETSKA OPTIMIZACIJA

Računanje ustaljenih in prehodnih stanj v realnem času je bilo v tem delu izhodišče eksjeretski optimizaciji. Računanje smo izpeljali z naslednjo družino enačb.

Kontinuitetna enačba:

$$(A\rho)_t + (A\rho v)_\xi = 0 \quad (1),$$

$$0 \leq \xi \leq L; t \geq 0 \quad (2).$$

Gibalna enačba:

Momentum balance equation:

$$v_t + vv_\xi + \frac{p_\xi}{\rho} + gh_\xi + \frac{(f)}{(2D_1)} v |v| = 0 \quad (3).$$

Gas control subsystem (GCS) is defined by the smallest time scale needed to make a record of all field metered values (such as pressure, flow rate, temperature etc.). It is directly concerned with the system elements such as remote stations to enable the observer to change the pressure and flow rate. The gas modeling subsystem (GMoS) utilizes standard transport equations for the real-time steady state and transient simulation of gas flow. The results of numerical solution are on-line compared with metered values. This subsystem enables also gas inventory and pressure predictions for the future whenever gas delivery is known. The gas inventory difference between the maximum and minimum pressure profile is called the line pack. The line pack changes with time because of the uncorrelated dynamics of gas off take and supply. A gas management subsystem (GMS) deals with the data far into the future. It uses forecasting methods to minimize the quantity of data but still allows the observer to have the best possible information [5]. This is achieved with the selection of appropriate time scales. Although the GMS can act as an independent system, its optimal role can be achieved when integrating load/supply forecast (probabilistic methods) and inductive decision making to describe the impact of the narrower environment on the line pack. This could be done when utilizing the fluid mechanical exergy concept. The closure problem of such a system has been solved by an unique linking through different time windows. Intelligent interfaces have been developed to make these links possible⁷.

3 EXERGETIC OPTIMIZATION

Real-time calculation of steady states and transient states was the keystone of exergetic optimization in this work. This calculation was performed by the following set of transport equations.

Mass balance equation:

Energijska enačba:

$$\rho c_v (T_t + v T_\xi) = - T \left\{ \frac{\partial p}{\partial T} \right\}_\rho v_\xi + \rho \frac{(f)}{(2D_1)} |v|^3 - \frac{(4U_w)}{(D_1)} (T - T_g) \quad (4),$$

spr. notranje energ. ekspanzijski učin. viskozne izg. prenos topote
int. energy change expansion effects viscous losses heat transfer

Pri tem so:

Above:

$$v_\xi = \frac{1}{c^2} \frac{\dot{p}}{p}; \quad \dot{p} = \frac{\partial p}{\partial t} + v \frac{\partial p}{\partial \xi} \quad (5).$$

$$v_t = \frac{1}{\rho A} \dot{m}; \quad \dot{m} = \frac{\partial m}{\partial t} + v \frac{\partial m}{\partial \xi} \quad (6).$$

Sklenitev teh transportnih enačb zahteva še dodatne konstitucijske enačbe, ki opisujejo trenje, stanje plina, toplotne kapacitete in molsko maso.

Integracija enačbe (4) v mejah največjega in najmanjšega dopustnega tlachenega profila opredeluje ekspanzijske učinke kot mehansko eksergijo plina (potrebna energija po Evansu, ki označuje obliko energije, potreben za opravljanje dela [10]). Eksersetska analiza zahteva sklenitev, ki vključuje vse dele okolice sistema, ki vplivajo na termodinamske spremenljivke v (4). Rešitev problema je zahtevna, ker lastnosti okolice ni tako preprosto definirati. Cilj eksersetske optimizacije v GMoS je povečati kakovost storitve sistema GTS na največjo mogočo mero (povečati pretočnost, optimalno preklapljanje mreže) pri minimalnih stroških transmisije. Zmanjšanje celotnih stroškov Γ_s na najmanjšo mogočo mero za dano storitev GTS omogoča določevanje meje med ožjo in širšo okolico. Namesto Tribusovega potenciala, ki bi ga lahko uporabili pri pogojih z eno samo skalo, je bil uporabljen naslednji algoritem iterativnega postopka prek različnih časovnih okvirjev [8].

Additional constitutive relations on friction, fluid state, heat capacities, and molecular weight were needed to close the set of transport equations.

Integration of eq. (4) within the limits of the maximum and minimum allowable pressure profile stipulates expansion effects as fluid mechanical exergy (essergy, after Evans a contraction of essential energy — signifying energy in the form essential for power production [10]). Analysis in terms of exergy requires closures which include all portions of the system environment which affect the thermodynamic variables in (4). The problem is difficult to solve, since the environmental properties are not easy to define. The objective of exergetic optimization under GMoS is to maximize the quality of GTS system performance (maximization of throughput, optimal switching of network) by minimizing the transmission costs. Minimizing the overall costs Γ_s for a given GTS performance helps us to define the boundaries of the narrower environment. Instead of Tribus thermoeconomic potential, which could have been implemented under single-scale conditions, the following optimization algorithm was used by iterative procedure over different time-frames [8].

$$\text{Minimiziraj } \Gamma_s = \sum_{I=1}^I \Gamma_{GPU,I} \int_{t_0}^{t_e} W_I(t) dt + \sum_{J=1}^J P_j \int_{t_0}^{t_e} \Gamma_{EGT,J}(t) W_j(t) dt \\ \text{Minimize } \{x\}$$

$$+ \sum_{k=1}^K P_k \int_{t_0}^{t_e} \Gamma_{GS,k}(t) W_k(t) dt + \sum_{l=1}^L \int_{t_0}^{t_e} \Gamma_{SGT,l}(t) W_l(t) dt \quad (7).$$

Stroški dobave Γ	indeks nomencl.	objekt entity	časovna skala time scale τ
<i>Zunanji (ožja okolica): External (narrower environment):</i>			
<i>pridobivanje plina gas production</i>			
nakup plina*	GPU	i	leto, mesec year, month
gas purchase			
zunanji transport*	EGT	j	leto, ura year, hour
external gas transport			
skladišče plina*	GS	k	leto, ura year, hour
gas storage			
<i>Notranji (sistem): Internal (system):</i>			
<i>kompresorske postaje compressor stations</i>			
transport plina v sistemu*	SGT	i	ura hour
system gas transport			
vzdrževanje cevovoda pipeline maintenance			
notranja kapaciteta*	—	LP	ura hour
line pack			

* ustreza trenutni konfiguraciji slovenskega plinovodnega sistema

applies to the present Slovenian gas transmission system

Algoritem je moč uporabiti pri uspešnem povezovanju GCS, GMoS and GMS. Ta način, v primerjavi s filozofijo Ranta in Tribusa, omogoča izogibanje pojavu zamrznjenih spremenljivk in tem spremeljanje dinamičnih procesov na več skalah.

Sklenitve

$$W(t) = A\rho v \quad (8).$$

$$\sum_{I=1}^I A(\tau) W_I + \sum_{k=1}^K \int_{t_0}^{t_\tau} W_k(t) dt_h + \sum_{I=1}^L \int_{t_0}^{t_\tau} W_{LP,I}(t) dt_h = \sum_{I=1}^L \int_{t_0}^{t_\tau} W_{IF\tau}(t) dt_\tau \quad (9),$$

kjer je $W_{IF}(t)$ napoved obremenitve pretokov. Uporabljene statistične metode so odvisne od okvira τ .

Letna bilanca: $t_\tau = 1$ leto, $dt_\tau = 1$ mesec

$$\sum_{k=1}^K \int_{t_0}^{t_y} W_k(t) dt_h = 0 \quad (10),$$

$$\sum_{I=1}^L \int_{t_0}^{t_y} W_{LP}(t) dt_h = 0 \quad (11),$$

This could be done only by successful linking of GCS, GMoS and GMS. In distinction to the philosophy by Rant and Tribus, this approach enables the avoidance of the appearance of frozen variables and therefore enables multiscale dynamic processes to be followed.

Closures

where $W_{IF}(t)$ is a load forecast flow rate. The statistical methods are dependent on τ frame.

Yearly balance: $t_\tau = 1$ year, $dt_\tau = 1$ month

Mesečna bilanca: $t_{\tau} = 1$ mesec, $dt_{\tau} = 1$ dan

Monthly balance: $t_{\tau} = \text{month}$, $dt_{\tau} = 1$ day

$$\sum_{k=1}^K W_k(t) \leq W_P \quad (12),$$

$$\sum_{l=1}^L \int_{t_0}^{t_m} W_{LP}(t) dt_h = 0 \quad (11).$$

Dnevna bilanca: $t_{\tau} = 1$ dan, $dt_{\tau} = 1$ ura

Daily balance: $t_{\tau} = 1$ day, $dt_{\tau} = 1$ hour

$$\sum_{i=1}^I A(\tau) W_i(t) + \sum_{k=1}^K W_k(t) \leq \sum_{j=1}^J W_j(t) \quad (14),$$

$$p_{\min,1} \leq p(\xi) \leq p_{\max,1} \quad (15).$$

Zmanjšanje celotnih stroškov Γ na najmanjšo možno mero vodi v izkoriščanje mehanske eksergije plina v največji mogoči meri. Zahteve v (7) zato preidejo v:

$$\begin{aligned} & \text{Maksimiraj } \dot{p}_1 \\ & \{x\} \end{aligned}$$

Optimizacijski postopek v realnih razmerah je pokazal, da je dinamiko odjemov mogoče spremljati na različnih skalah [8]. Linearni, interaktivni in diskretni optimizator je bil uporabljen za določanje optimalnih vrednosti vnaprej. Od tod so bile izpeljane vrste dejavnosti na ustreznih časovnih skalah. To je omogočilo nadaljnjo optimizacijo v letnem, mesečnih in dnevnih okvirih.

4 SKLEPI

Opravljene so bile študije razpozname, konstruiranja in upravljanja visokotlačnega plinovodnega sistema. Računanje ustaljenih in prehodnih stanj v realnem času je bilo izhodišče eksferske optimizacije. Način je izviren v:

- strukturiranju elementov in procesov sistema,
- ločevanju skal — razgrajevanju procesov, ki omogoča optimizacijo na različnih ravneh,
- izvajanju optimizacije procesov, ki se odvijajo na različnih časovnih skalah hkrati.

Minimization of overall costs leads towards maximization of fluid mechanical exergy utilization. Hence, the requirements in (7) transform into:

$$\begin{aligned} & \text{Maximize } \dot{p}_1 \\ & \{x\} \end{aligned}$$

The optimization process in a real field showed that the offtake dynamics could be followed on several time scales [8]. A linear, interactive and discrete optimizer was used to define optimal values in advance. From that, the compositions of activities according to the corresponding time scales were made. This enabled a further optimizing procedure on yearly, monthly and daily frames.

4 CONCLUSIONS

Studies of complex system identification, design, control and management were undertaken on a high pressure gas transmission system. The real-time calculation of steady and transient states was the keystone of exergetic optimization. The approach is unique in:

- structuring the system elements and processes,
- scale separation process decomposition so that optimization is possible on different levels.
- operating cost optimization on different time scales by running the processes simultaneously.

5 OZNAČBE

A	– površina prečnega prereza cevi
D_1	– notranji premer cevi
P	– utežna funkcija kapacitete skladišča
T	– temperatura plina
T_g	– temperatura zemlje
U_w	– povprečni koeficient prenosa toplotne
W	– kupljene količine plina
$W(t)$	– pretok
$W_F(t)$	– napovedane obremenitve pretoka
τ	– časovna skala
Δ	– krajevna skala
c_v	– izohorna specifična toplotna plina
f	– Moodyjev faktor trenja
g	– gravitacijski pospešek
h	– nagib cevi
p	– tlak plina
t_0, t_e	– začetni čas, končni čas
v	– hitrost plina
{x}	– vrsta odločitvenih spremenljivk
ξ	– lega vzdolž cevi
ρ	– gostota plina
Γ_s	– cena dobave na enoto pretoka

5 SYMBOLS

A	– cross-sectional area of the pipe
D_1	– internal pipe diameter
P	– storage capacity weight
T	– temperature of the gas
T_g	– ground temperature
U_w	– overall heat transfer coefficient
W	– purchased gas quantity
$W(t)$	– flow rate
$W_F(t)$	– load forecast flow rate
τ	– time scale
Δ	– length scale
c_v	– heat capacity of the gas
f	– Moody friction factor
g	– gravity acceleration
h	– elevation of the pipe
p	– pressure of the gas
t_0, t_e	– beginning, ending time
v	– velocity of the gas
{x}	– a set of decision variables
ξ	– position along the pipe
ρ	– density of the gas
Γ_s	– supply cost per unit flow rate

¹ Kadarkoli Q opazuje P , primerja svojo (izbrano) časovno skalo τ_Q in krajevno skalo Δ_Q z množico časovnih skal τ_Q in krajevnih skal Δ_P , ki se pojavijo po naravnih zakonitostih v P zaradi interakcij med elementi.

τ_Q in Δ_Q sta odvisna od opazovalčeve objektivnosti in znanja in lahko postavita v žarišče samo določeni skali τ_{Pi} in Δ_{Pi} . Konstitucija P , ki jo vidi opazovalec, je zato reje omejena z okviroma τ_Q in Δ_Q .

² Letalo, na primer, ni le skupek obdelanega materiala, ampak je konstruirano tako, da celoten sistem lahko leti. Kakovost opravljene storitve sistema narašča iz leta v leto z dodajanjem nekaterih novih koherenčnih sklopov.

³ Če nadrobneje pogledamo omenjeno letalo, lahko seznanje zraka na zgornji površini krila zmanjšuje debelino mejne plasti z odvzemanjem plasti zraka z majhno gibalno količino ob površini krila. Pojavlji se stabilnejša mejna plast s kasnejšim prehodom v turbulentco. To zmanjšuje prečne izgube gibalne količine v brazdi. Jasno je, da za takšno zmanjšanje polja zavirnih sil potrebujemo energijo. Optimalni pogoji so doseženi, ko je celotna zaviralna sila, aerodinamska z dodatnim ekvivalentnim deležem porabljeni moči, najmanjša.

⁴ τ_Q je lahko zmanjšan samo, če ima Q večji vpogled v obnašanje P , kakor je prikazano v prvotnem prostoru stanj. Zamislimo si, da je za dani τ_Q prostor stanj določen z $X(\tau_Q)$. Pomanjšanje τ_Q na τ'_Q zahteva razširjen prostor stanj $X'(\tau'_Q)$, ki vsebuje $X(\tau_Q)$ kot podprostор, če obdržimo v spremenljivkah le X , ki lahko postanejo s pomanjšanjem τ_Q zamrznjene. Neravnotežni proces v $X(\tau_Q)$ se bo pojavil kot ravnotežni v $X'(\tau'_Q)$, če je izpolnjen pogoj $\tau'_Q \sim dt \ll \tau_Q$ [3].

¹ Whenever Q observes P , he compares his (chosen) time τ_Q and length Δ_Q scales with the variety of time τ_Q and length Δ_P scales occurring naturally in P due to system elements interactions. τ_Q and Δ_Q depend upon the observer's aims and knowledge and can focus on only particular τ_{Pi} and Δ_{Pi} . The P constitution, as seen by the observer, is therefore constrained by τ_Q and Δ_Q frames.

² For example, instead of being merely an aggregation of shaped materials, an airplane is constructed so that the entire system can fly. The quality of system performance is constantly increased by the accumulation of coherent structures over the years of development.

³ If one considers the aforementioned airplane, the suction of air on the upper surface of the airfoil reduces the thickness of the boundary layer by removing the low-momentum fluid next to the surface. A more stable layer results, and transition to turbulence is delayed. This reduces the streamwise momentum loss in the wake. It is obvious that power is needed to achieve this drag reduction. The optimum condition occurs when the total drag — the aerodynamic drag plus the suction power converted to an equivalent drag — is at a minimum.

⁴ τ_Q can be reduced only if Q has a greater insight into the behavior of P than represented in the original state-space. Suppose for a given τ_Q the state space is $X(\tau_Q)$ then if we agree to retain in X any variables that could be frozen by reducing τ_Q , the reduction of τ_Q to τ'_Q requires an extended state space $X'(\tau'_Q)$ containing $X(\tau_Q)$ as a sub-space. Then if $\tau'_Q \sim dt \ll \tau_Q$ a non-equilibrium process in $X(\tau_Q)$ will appear as an equilibrium process in $X'(\tau'_Q)$ [3].

⁵ Entropija S se pojavi v prostoru stanj X z vpeljavo povračljivega adiabatnega procesa $X_1 \leftrightarrow X_2$, za katerega velja $S_2 - S_1 = 0$. Če vpeljemo vmesno stanje $X'_Q(\tau_Q)$, ki izpade neravnotežno na večji časovni skali τ_Q , se lahko z gotovostjo soočimo z entropijo kot veličino stanja $S'(X')$, toda ker je X' nedefiniran na časovni skali τ_Q , ostaja vrednost S' opazovalcu Q nepoznana. Dejanska vrednost S je zatoj odvisna od opazovalčeve skale τ_Q [3].

⁶ To bi lahko pomenilo dodatno osvetlitev drugega zakona inženirske termodinamike. Z namenom izboljšati gospodarske učinke bi to lahko tudi vodilo v nadaljevanje zamisli del Ranta [4] in Tribusa [6]. Pri tem velja omeniti, da se je v tistem času pojavila tudi razprava, ali naj se termodinamski principi družijo z ekonomskimi ali ne. Naše izkušnje na »termoekonomske« aplikacijah plinovodnega sistema so pokazale, da je koncept eksergije oz. potrebne energije, kakov ga je imenoval Evans [10], zelo uporaben. Zato se pridružujemo filozofiji, da mora biti sistem korektno definiran nasproti okolici, kar se pri praktičnih inženirskih aplikacijah prej ali slej konča z ekonomskimi omejitvami.

⁷ Vmesnik za GCS in GMoS omogoča prenos vhodnih in izhodnih podatkov v realnem času (na podlagi sprejemnega protokola) v stalen tok podatkov, ki jih zahtevajo transportne enačbe in hkrati ločuje slabe podatke od dobrih. Vmesnik za usklajevanje GCS, GMoS in GMS sinhronizira upravljanje, procesne napovedi in uravnavanje nastavitev vrednosti. Podatki o nastavitevih vrednostih, ki določajo dobavne količine plina, so uporabni kot trenutna referenca za GCS [8].

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⁵ The entropy function S is introduced into state-space X via reversible adiabatic processes $X_1 \leftrightarrow X_2$, for which $S_2 - S_1 = 0$. If we introduce an intermediate state $X'_Q(\tau_Q)$, which is in non-equilibrium on the longer time scale τ_Q , we may certainly envisage an entropy state variable $S'(X')$, but as X' is undefined on the time scale τ_Q , the value of S will be unknown to the observer Q. The actual value of S depends on Q's time scale τ_Q [3].

⁶ This might shed new light on the second law of engineering thermodynamics. If applied to improve economical effects this may also lead towards an extension of the concepts of Rant [4] and Tribus [6]. There has been discussion on whether the principles of thermodynamics may be merged with the principles of economics. It is beyond the scope of this paper to discuss this matter. Our experience in »thermoeconomic« application in gas transmission systems has proved, however, that the concept of exergy or essergy (after Evans [10]) can be very useful. We therefore follow the philosophy that a system should be properly defined with respect to its environment, which in practical engineering applications sooner or later ends up with economic constraints.

⁷ The GCS/GMoS interface transfers the real time I/O data (based on report by exception) to the constant data flow rate required by the transport equations, and discriminates between good and bad values. The GCS/GMoS/GMS interface synchronizes management optimization, the prediction process and set point balancing. Set point data which control the gas supply flow rates serve as an instant reference to GCS [8].

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