© Strojniški vestnik 46(2000)8,525-531
ISSN 0039-2480
UDK 532.5:621.644:697.4
Pregledni znanstveni članek (1.02)

© Journal of Mechanical Engineering 46(2000)8,525-531
ISSN 0039-2480
UDC 532.5:621.644:697.4
Review scientific paper (1.02)

Zmanjšanje tlačnih izgub v vročevodnih cevnih mrežah

The Reduction of Friction Losses in District-Heating Pipelines

Andrej Krope - Jurij Krope - Igor Tičar

V prispevku je predstavljen vpliv kationskih površinsko aktivnih dodatkov na zmanjšanje intenzivnosti turbulence v ceveh primarnih vročevodnih mrež sistemov za daljinsko ogrevanje. Že zelo majhne količine dodatkov vroči vodi, povzročijo znatno zmanjšanje odpora pri pretoku po ceveh in zato manjše izgube tlaka, kar vodi do manjše potrebne moči črpalk, znižanja črpalnih stroškov, povečanja zmogljivosti, zmanjšanja stroškov plina za ogrevanje vode in zmanjšanja toplotnih izgub. Pri načrtovanju in izgradnji novih vročevodnih mrež lahko uporabljamo cevi z manjšimi premeri in tako znatno znižamo investicijske stroške.

(Ključne besede: pretok fluida, izgube tlačne, dodatki, sistemi toplovodni)

In the paper the impact of cationic surfactant additives on reducing the turbulence intensity in the hot-water pipelines of district heating systems is presented. With small amounts of cationic surfactants in district-heating water the friction losses in pipelines can be reduced significantly. Because of this effect the pressure drops are decreased what leads to reductions in pump energy, pumping costs, costs of gas for heating the supply water, heat losses and to an increase in the heat capacity. New district-heating networks can be designed with smaller pipe diameters and so investment costs can be reduced significantly by applying friction-reducing additives.

(Keywords: fluid flow, pressure drops, additives, heating pipelines)

0 UVOD

Zmanjšanje zalog primarnih goriv in s tem v zvezi varčevanje z energijo terja na področju toplotne tehnike iskanje novih tehnično-znanstvenih spoznanj, kar je v zadnjem času pomembna tema številnih državnih in mednarodnih raziskovalnih projektov. Težišče raziskav temelji na boljšem izkoriščanju primarne energije.

Energetski sistemi za daljinsko ogrevanje zagotavljajo prihranke pri porabi primarne energije in ekološko sprejemljivo oskrbo s toplotno energijo [1]. Z ekonomskega vidika gre v primeru daljinskega ogrevanja za nasprotje med nizkimi stroški proizvodnje toplotne energije in relativno visokimi prenosnimi in razdeljevalnimi stroški. Večino stroškov, povezanih s sistemi daljinskega ogrevanja pomenijo naložbe v cevno mrežo ter stroški črpanja. Zaradi tega so sistemi daljinskega ogrevanja cenovno razmeroma ugodni le pri majhnih pretočnih razdaljah. Ena od možnosti za izboljšanje učinkovitosti in gospodarnosti takšnih sistemov je dodajanje snovi za

0 INTRODUCTION

Decrease of primary energy supplies and in this connection saving with energy demands investigations for new technical-scientific cognition in the field of heat engineering, what is an important topic of numerous national and international research projects particularly in recent years. The centre of this researches is more rational exploitation of primary energy.

District-heating systems ensure savings by consumption of primary energy and ecological heat-energy supply [1]. From the economic point of view there is a contradiction between low heat-generation costs and relatively high transport and distribution costs of district heat. The investments in pipelines and pumps, together with the pumping costs, form a major cost item of district-heating systems. For this reason the costs for such systems are relatively favourable only at short transport distances. One of the possibilities to improve effectiveness and economic viability of district-heating systems is applicazmanjšanje odpora pri pretoku tekočin. Na ta način lahko znatno zmanjšamo tlačne izgube, povečamo pretok in s tem prenos toplotne energije, kar vodi do občutnega znižanja naložb v cevi in črpalke ter znižanja stroškov električne energije, ki je potrebna za pogon črpalk. Zmanjšanje tlačnih izgub se kaže tudi v primernejši rabi primarne energije in nižji obremenitvi okolja.

Vpliv majhnih količin dodatkov vodi na odpor pri pretoku tekočin in padec tlaka v ravni cevi je že leta 1948 odkril Toms [2]. Od tedaj je bilo izvedenih že na stotine preskusov, ki so potrdili takratno odkritje. Značilnosti tega pojava so naslednje:

– pri pretoku vode v ceveh je mogoče z dodatkom raztopine dodatka koncentracije 5 ppm zmanjšati odpor za 70 %,
– večje znižanje odpora se pojavlja le pri turbulentnem toku,
– z dodatkom raztopine dodatka je mogoče povečati pretok za 30 %,
– raztopine dodatkov so učinkovitejše pri ceveh manjšega premera.

V preteklosti so za znižanje odpora uporabljali različne polimerne dodatke z veliko molekulsko maso, vendar so se ti izkazali za manj uporabne zaradi nepovračljive razgradnje, ki se pojavi pri velikih strižnih silah. Danes se za znižanje odpora v vročevodnih cevnih sistemih uporabljajo kationski površinsko aktivni dodatki majhnih molekulskih mas, ki povzročajo znižanje tlačnih izgub že v zelo majhnih koncentracijah in imajo povračljivo strukturo.

1 DELOVANJE KATIONSKIH POVRŠINSKO AKTIVNIH DODATKOV

Učinek zmanjšanja viskoznosti in s tem odpora pri pretoku tekočin, ki ga povzročajo vodne raztopine dodatkov, temelji na zmanjšanju intenzivnosti turbulence in ga lahko pojasnimo s tvorbo in oblikovanjem micelijev.

Površinsko aktivni dodatki so nizkomolekularne snovi z majhno kemijsko aktivnostjo in nizko topnostjo, ki so sestavljene iz hidrofilnega in hidrofobnega dela [3]. Kadar so takšne molekule v vodi ali v topilu, ki ima podobne lastnosti kakor voda, se pod določenimi pogoji združejejo v združbe, ki jih imenujemo miceliji. Miceliji so aglomerati nekaj sto molekul in lahko imajo različne oblike; lahko so okrogli, palični ali pa ploščati. Potrebni pogoj za zmanjšanje odpora so palični miceliji. Kritično micelarno koncentracijo, nad katero se molekule dodatka združujejo v micelije, prikazuje slika 1. Če je v vodni raztopini dodatka presežena koncentracija CMC_1, pride do tvorbe krogelnih micelijev s premerom približno dvakratne dolžine posamezne molekule. Ta koncentracija je le malo odvisna od temperature. Če

tion of friction-reducing additives in hot-water supply pipelines. In this way pressure drops can be significantly reduced and the flow rate can be increased enabling a reduction in the investment in pipelines and pumps and savings in the costs of electrical energy used for drive of pumps. A reduction of friction loss is also shown to be more rational consumption of primary energy and results in a impact on the environment.

As early as 1948 Toms [2] reported on friction loss and pressure drop when minute amounts of soluble polymer additive where added to water flowing through a straight pipeline. Since then, hundreds of experiments have confirmed his initial findings. The essential features of this phenomenon are as follows:

– the friction loss of water flow in pipelines can be reduced as much as 70% with additives in concentrations as low as 5 ppm,
– significant reductions in friction loss occur only for turbulent flow,
– additives can increase the flow rate by 30%,
– additive solutions are more effective on small pipelines than on large ones.

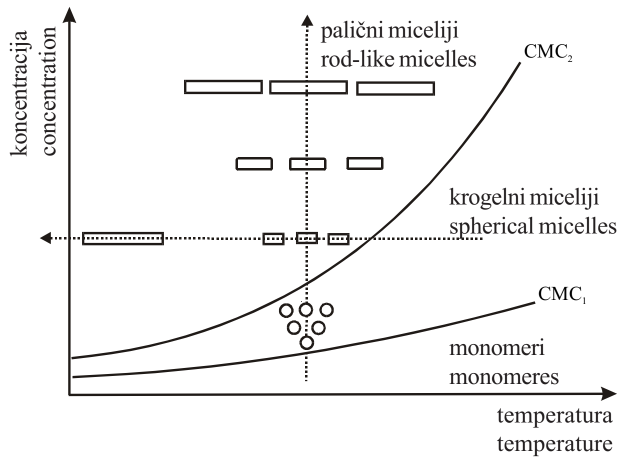
In the past a variety of polymer-based additives with high molecular weight have been used for reducing the friction losses, however, they have proved as less applicable because of their irreversible degradation which occurs at high values of shear stress. Nowadays, low molecular cationic surfactant additives, which effect on reduction of pressure drops already in small quantities and have reversible structure, are used for drag reduction in hot-water-pipe systems.

1 OPERATING PRINCIPLE OF SURFACTANTS

The phenomenon of friction reduction with surfactants in aqueous solutions is based on the decrease of the turbulence intensity and can be explained with the formation and the shape of micelles.

Surfactants are low-molecular-weight substances with low chemical activity and low solubility, but great interfacial activity. The molecules consist of a hydrophilic group and a hydrophobic part [3]. Under certain conditions the surfactant monomers form micelles in aqueous solutions. Micelles are clusters of approximately a hundred surfactant molecules and can take any of a variety of shapes, such as spheres, bars or disks. The presence of rod-like micelles is considered to be a necessary condition for the friction-reducing effect. Critical micelle concentrations, above which surfactant molecules form micelles, are shown in Figure 1. When the critical micelle concentration (CMC_1) in an aqueous solution is exceeded the surfactants form spherical micelles. This concentration is almost temperature independent. If the concentration is increased still further, the se koncentracija še naprej povečuje, se število molekul dodatka na micelij povečuje, dokler ni celotna prostornina micelija popolnoma izpolnjena z ogljikovimi verigami. Ko je presežena koncentracija CMC_2, tvorijo dodatki palične micelije, ker je takšna prostorska oblika energijsko ugodnejša. Dolžina paličnih micelijev se povečuje z naraščajočo koncentracijo. Kritična koncentacija CMC_2 je močno odvisna od temperature.

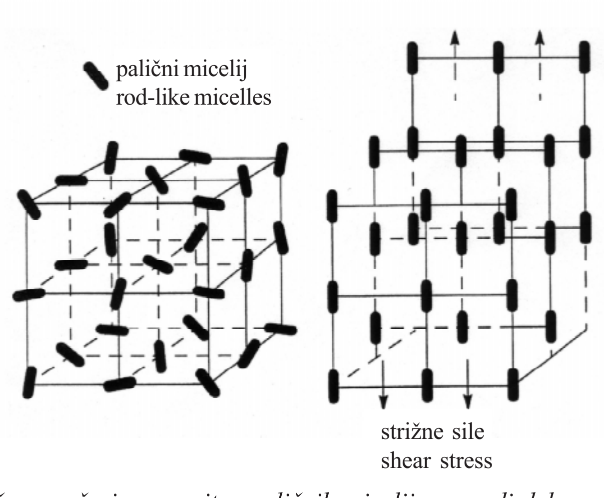
number of surfactant molecules per micelle will increase until the micelle volume is completely filled with carbon chains. When the second critical micelle concentration (CMC_2) is exceeded the surfactants form rod-like micelles, because these boundary faces are more energetically favourable. The length of bar-shaped micelles increases with increasing concentration. The CMC_2 concentration is strongly temperature dependent.



Sl. 1. *Kritična micelarna koncentracija [3]*
Fig. 1. *Critical micelle concentrations [3]*

Vodne raztopine dodatkov, ki tvorijo krogelne micelije se obnašajo podobno kakor voda, viskoznost takih raztopin je včasih celo večja od viskoznosti čiste vode in zato ne povzročajo učinka znižaja odpora pri pretoku tekočine. Pri koncentracijah, večjih od CMC_2, pa se v raztopini dodatka oblikujejo palični miceliji, ki kažejo viskoelastično obnašanje. Takše celice micelijev se zaradi turbulentnega toka in strižnih sil usmerjajo v smeri toka in tvorijo viskoelastično prostorsko mrežo, ki razširi prehodni sloj in zmanjša turbulentno jedro glavnega toka (sl. 2).

Aqueous surfactant solutions that form spherical micelles behave in the same way as the water, at high concentrations the viscosity becomes somewhat higher than that of the water, so this clusters do not perform friction-reducing effect. At concentrations that are higher than CMC_2, the surfactant solutions in which rod-like micelles have formed exhibit a favourable viscoelastic behaviour. Such cells become oriented by the pulse loads of turbulent flow and form a permanently oriented viscoelastic network which expands the buffer layer and reduces the layer of turbulent main-stream flow (Fig. 2).



Sl. 2. *Viskoelastična mreža in usmeritev paličnih micelijev zaradi delovanja strižnih sil [3]*
Fig. 2. *Viscoelastic network, orientation of micelles, shear induced structure [3]*

Pri koncentracijah okoli CMC_2 se oblikuje le nekaj relativno velikih micelijev, ki pa so le omejeno sposobni oblikovati usmerjene mreže, zato je njihov vpliv na znižanje odpora majhen. Za zadovoljivo znižanje je zato potrebna večja koncentracija, ki povzroči trajno usmerjene viskoelastične mreže, ki dušijo razvijanje turbulentnih vrtincev in tako povzročajo laminarni tok.

Funkcionalno odvisnost vodnih raztopin kationskih površinsko aktivnih dodatkov od Reynoldsovega števila prikazuje slika 3, na kateri opazimo 4 različna področja [4]:

⇒ Področje I: v laminarnem področju toka z majhnimi strižnimi silami ali brez njih oblikujejo palični miceliji prostorsko mrežo z elektrostatskim odbojem, ki je posledica njihovega površinskega naboja, in v njej zasedejo energetsko ugodna mesta. V tem stanju se raztopine površinsko aktivnih dodatkov obnašajo kot newtonske tekočine.

⇒ Področje II: povečanje strižnih sil in turbulentni tok vplivata na usmerjanje micelijev in oblikovanje viskoelastične mreže, kar povzroča laminaren tok. V tem stanju se raztopine površinsko aktivnih dodatkov obnašajo kot pseudoplastične tekočine.

⇒ Področje III: nadaljnje povečevanje strižnih sil vpliva na povečanje učinka zniževanja odpora. Miceliji so zmožni sprejeti več energije, ker deformiranje in raztezanje mreže povzroča sile, ki delujejo proti turbulentnemu vrtinčastemu gibanju in zato manjšajo oddajo energije. V tem področju je, ob uporabi dodatka, katerega delovno območje se ujema z obratovalnimi razmerami v sistemu daljinskega ogrevanja, učinek znižanja odpora neodvisen od koncentracije vodne raztopine dodatka. Raztopine dodatkov se tudi v tem področju obnašajo pseudoplastično, vrsto toka, ki se pojavi v takšnih razmerah pa imenujemo pseudolaminarni tok.

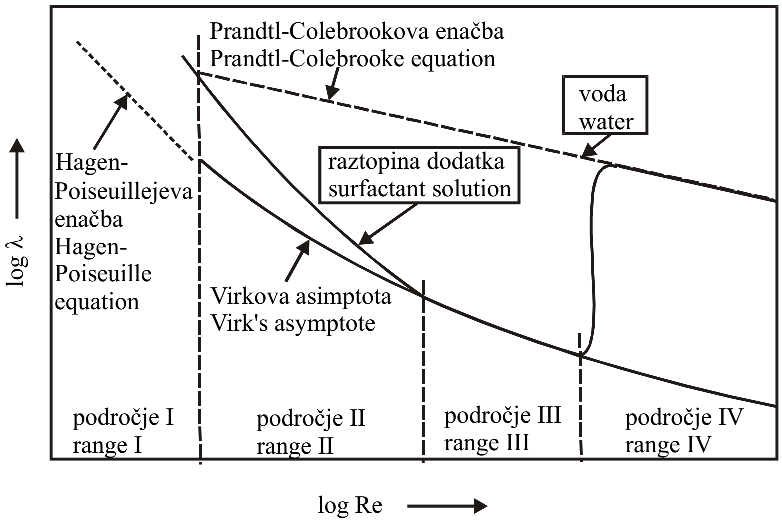
If the concentration is only just above CMC_2, then only few relatively large micelles will be formed. These micelles are not well capable of forming an oriented network, which is why their friction effect is only small. Therefore, for a significant reduction of friction losses a higher concentration is required. These concentrations generate permanently oriented viscoelastic networks which suppress the formation of turbulent whirls and produce a laminar flow in this way.

The functional relationsip between surfactant-solution behaviour and Reynolds number is shown in Figure 3, where we can see four different ranges [4]:

⇒ range I: In the laminar region of flow with little or no shear stress the rod-like micelles form a spatial network with the electrostatic repulsion caused by their surface charge, in which they occupy energetically favourable positions. In this state the surfactant solution shows Newtonian behaviour.

⇒ range II: A rise of shear stress and turbulent flow lead to orientation of the rod-like micelles and formation of the viscoelastic network what causes laminar flow. In this range the surfactant solution shows pseudoplastic flow behaviour.

⇒ range III: A further rise in shear stress leads to an increase in friction reduction. In this range the maximum reduction of friction losses appears. Micelles are able to incorporate more energy because deforming and stretching causes reset forces which act against the turbulent fluctuation movement and therefore reduce the energy dissipation. In this range pseudoplastic behaviour exist as well and this flow condition is known as pseudolaminar flow.



Sl. 3. *Darcyjev koeficient linijskih izgub v odvisnosti od Reynoldsovega števila za vodne raztopine dodatkov [4]*
Fig. 3. *Darcy's friction coefficient with its dependence on the Reynolds number for aqueous surfactant solution [4]*

⇒ Področje IV: zelo visoke strižne sile, ki jih povzroča povečana hitrost toka povzročijo razpad viskoelastične micelarne mreže in s tem konec vpliva dodatkov na znižanje odpora. Značilna krivulja raztopine dodatka doseže krivuljo vode. V tem področju nastane celovit turbulentni tok, raztopine površinsko aktivnih dodatkov se ponovno obnašajo kot newtonske tekočine.

Hkrati s pozitivnim učinkom znižanja odpora se pri uporabi dodatkov, zaradi spremenjenih pretočnih razmer (newtonsko obnašanje tekočine zamenja pseudoplastično) pojavijo tudi negativni učinki: to so zmanjšanje prenosa toplote, korozija in onesnaževanje okolja [1]. Problem zmanjšanega prenosa toplote rešujemo z modeliranjem vrste in lokacije prenosnikov toplote ter tako, da v menjalnike vstavljamo pregrade, ki povečujejo turbulenco in s tem prenos toplote. Novejše raziskave so pokazale, da kombinirani površinsko aktivni dodatki s tržnimi imeni Habon G / NaSal, Obon G / NaSal in Dobon G / NaSal ne kažejo nobenega vpliva na korozijo materialov, ki se uporabljajo v sistemih daljinskega ogrevanja. Problem strupenosti dodatkov in s tem povezanega onesnaževanja okolja rešujemo tako, da jih uporabljamo le v zaprtih sistemih s posredno povezavo obrata za proizvodnjo toplote in porabnikov prek toplotnih postaj in sekundarne mreže.

⇒ range IV: Very high shear rates finally affect the destruction of the viscoelastic micelle network so that the friction-reducing effect disappears and the characteristic surfactant solution curve approaches that of water. In this case a fully developed turbulent flow appears, which again shows Newtonian behaviour.

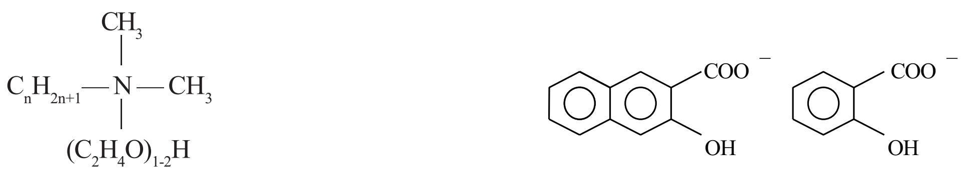
As well as the positive effects of drag reduction, negative effects due to the change in flow behaviour (pseudoplastic behaviour instead of Newtonian) [1] like heat-transfer reduction, corrosion and contamination of environment also occur. The phenomenon of radial turbulence and the associated reduction of heat transfer in heat exchangers can be solved by installing turbulence-increasing obstacles inside the heat exchangers to improve the heat-transmission properties. Some new investigations have shown that combined cationic surfactants with the trade names Habon G / NaSal, Obon G / NaSal and Dobon G / NaSal do not show any impact on the corrosion rates of materials which are built in district-heating systems. The problem of contamination and pollution of environment can be solved by only using surfactants in closed transport systems with an indirectly connected heat-generation plant and consumer systems. This can be achieved with the installation of heat-transmission stations and secondary hot-water-pipe network.

2 KOMBINIRANI KATIONSKI POVRŠINSKO AKTIVNI DODATKI

Najboljše rezultate dosežemo s površinsko aktivnimi dodatki Habon G, Obon G in Dobon G v kombinaciji s snovjo NaSal, ki zagotavlja širše temperaturno področje delovanja. Kemijsko strukturo omenjenih dodatkov, ki so uporabni pri koncentracijah do 1500 utežnih ppm in hitrostih toka do 4 m/s, prikazuje slika 4.

2 COMBINED CATIONIC SURFACTANTS

The best results by reduction of friction losses in hot-water pipelines can be achieved with the cationic surfactant substances Habon G, Obon G and Dobon G in combination with the additional counter-ion NaSal, which ensures extended temperature range of operation. The chemical structure of above-mentioned surfactants, which can be used by concentrations up to 1500 wppm and flow velocities up to 4 m/s is shown in Figure 4.



n-Alcyldimethylpolyoxethylammonium – Cation

3-hydroxy-2-naphthoate   Salicylate

Sl. 4 *Kemijska struktura površinsko aktivnih dodatkov [3]*
Fig. 4. *Chemical structure of cationic surfactants [3]*

Temperaturno področje, v katerem omenjeni dodatki zagotavljajo znižanje odpora, je odvisno od števila ogljikovih atomov:
$n = 16$ (tržno ime Habon G / NaSal): od 25 do 105 °C
$n = 18$ (tržno ime Obon G / NaSal): od 35 do 120 °C
$n = 22$ (tržno ime Dobon G / NaSal): od 45 do 140 °C

The temperature range for which these surfactants show a friction-reduction effect depends on number of carbon atoms:
$n = 16$ (trade name Habon G / NaSal): from 25 to 105 °C
$n = 18$ (trade name Obon G / NaSal): from 35 to 120 °C
$n = 22$ (trade name Dobon G / NaSal): from 45 to 140 °C

3 DOLOČITEV EMPIRIČNE ENAČBE DARCYJEVEGA KOEFICIENTA TORNIH IZGUB

Dodatek kombiniranega dodatka Dobon G / NaSal v vročevodno cevno mrežo zniža odpor pri pretoku in povzroči zmanjšanje izgube tlaka. To znižanje odpora upoštevamo z enačbo, ki smo jo razvili v Laboratoriju za toplotno tehniko na Fakulteti za strojništvo Univerze v Mariboru [5]. Na temelju eksperimentalnih podatkov smo, z uporabo računalniškega programa Matlab in funkcije FMINS, ki izvaja Nelder-Meadov simpleks algoritem, določili odvisnost koeficienta tornih izgub (l) zaradi dodanega dodatka od Reynoldsovega števila (Re) v obliki potenče funkcije drugega reda z dvema linearnima in dvema nelinearnima koeficientoma v obliki (1):

3 DETERMINATION OF THE EMPIRICAL EQUATION OF DARCY'S FRICTION COEFFICIENT

The addition of the combined surfactant Dobon G / NaSal to hot-water-pipe network decreases the friction losses and reduce pressure drops in pipelines. This reduction of friction can be considered with the equation, which has been developed in our Laboratory for Heat Engineering at the University of Maribor, Faculty of Mechanical Engineering [5]. On the basis of experimental data and the help of The Matlab computer software with the FMINS function which performs Nelder-Meadov's simplex algorithm, the relationship between Darcy's friction coefficient (λ) and Reynolds number (*Re*) has been determined in form of a power function of the second grade with two linear and two non-linear coefficients (1):

$$\lambda = 0,17442 \cdot \mathrm{Re}^{-0,1989} - 0,00603 \cdot \mathrm{Re}^{0,001266} \qquad (1).$$

4 SKLEP

Uporaba dodatkov v sistemih daljinskega ogrevanja zagotavlja izboljšanje učinkovitosti in gospodarnosti obratovanja. Učinek zmanjšanja viskoznosti in s tem odpora, ki ga povzročajo vodne raztopine kationskih površinsko aktivnih dodatkov temelji na zmanjšanju turbulence in ga lahko pojasnimo s tvorbo in oblikovanjem paličnih micelijev. Pri koncentracijah, večjih od kritične koncentracije CMC_2, se v raztopini dodatka oblikujejo palični miceliji, ki kažejo viskoelastično obnašanje. Takšne celice micelijev se zaradi turbulentnega toka in strižnih sil usmerjajo v smeri toka in oblikujejo viskoelastično prostorsko mrežo, ki razširi prehodni sloj in zmanjša turbulentno jedro glavnega toka.

Zmanjšanje odpora pri pretoku tekočin ima za posledico zmanjšanje tlačnih izgub in zato znižanje stroškov električne energije za pogon črpalk, povečanje kapacitete, manjše stroške plina za ogrevanje vode in manjše toplotne izgube. Znižanje odpora pa se kaže tudi v manjši potrebni moči črpalk in nižji vrednosti naložbe v cevi z manjšimi nazivnimi premeri pri gradnji novega omrežja [6], kar omogoča oskrbo s toploto tudi v primeru večjih pretočnih razdalj. Treba pa je poudariti tudi pozitiven vpliv uporabe dodatkov na smotrno rabo energije in zaradi tega na manjšo obremenitev okolja.

4 CONCLUSION

The use of surfactants in district-heating systems results in an improvement in the system's operation. The effect of friction reduction, which is a result of the surfactants added to hot-water supply, is based on reduction of turbulence intensity and can be explained by the formation of rod-like micelles. At concentrations higher than the critical micelle concentration (CMC_2) the surfactants form rod-like micelles which show viscoelastic behaviour. Such micelle cells become oriented and form viscoelastic network because of the turbulent flow and shear stress. This shear-induced state expands the buffer layer and reduces the layer of turbulent main-stream flow.

The reduction of friction losses and the resulting reduced pressure drops lower the electrical energy costs for pump driving, the gas cost for heating the supply water and the heat losses while increasing the heat capacity. The reduction of friction is also reflected in a decreased pump energy and lower investment costs for hot-water pipelines, as new networks can be designed with smaller pipe diameters [6], or the maximum economic transport length can be increased. Likewise the positive effect of surfactant application is shown in more rational consumption of energy and consecutively lower charge of environment, what has to be mentioned, too.

5 LITERATURA
5 REFERENCES

[1] Krope, A. (1999) Optimiranje cevnih mrež z uporabo aditivov. Magistrsko delo (Master's thesis), *Faculty of Chemistry and Chemical Engineering, Maribor*, Slovenija

[2] Roberson, J.A., C.T. Crowe (1997) Engineering fluid mechanics, Sixth Edition. *John Wiley & Sons, Inc., New York, USA.*

[3] de Groot, M.C., E.A. Kievit (1996) The effects of surfactants on domestic heat exchangers for hot water supply and heat flow meters in D/H systems. *Technical University of Delft, Mechanical & Maritime Engineering, Thermal Power Engineering*, NOVEM, Sittard, The Netherlands.
[4] Weinspach, P.-M. (1996) Improving the heat transmission properties of tube bundle heat exchangers by installing obstacles inside the pipes; D1: Investigations of heat transfer and pressure drop. *Thermische Verfahrenstechnik GmbH,* Dortmund, Germany.
[5] Rupnik, A. (1997) Ekonomičnost uporabe aditivov v toplotnih sistemih daljinskega ogrevanja. *Magistrsko delo (Master's thesis), Faculty of Chemistry and Chemical Engineering*, Maribor, Slovenija.
[6] Krope, A, J. Krope, D. Goricanec: Optimal design of district heating networks operating with drag reducing additives. *Proceedings of the IASTED International Conference: Applied Modelling and Simulation,* Cairns, Australia, 1999.

Naslovi avtorjev: mag. Andrej Krope
Fakulteta za strojništvo
Univerze v Mariboru
Smetanova 17
2000 Maribor

prof.dr. Jurij Krope
Fakulteta za kemijo in kemijsko tehnologijo
Univerze v Mariboru
Smetanova 17
2000 Maribor

prof.dr. Igor Tičar
Fakulteta za elektrotehniko, računalništvo in informatiko
Univerze v Mariboru
Smetanova 17
2000 Maribor

Authors' Addresses: Mag. Andrej Krope
Faculty of Mechanical Eng.
University of Maribor
Smetanova 17
2000 Maribor, Slovenia

Prof.Dr. Jurij Krope
Faculty of Chemistry and Chemical Engineering
University of Maribor
Smetanova 17
2000 Maribor, Slovenia

Prof.Dr. Igor Tičar
Faculty of Electrical Engineering and Computer Science
University of Maribor
Smetanova 17
2000 Maribor, Slovenia

Prejeto:
Received: 15.8.2000

Sprejeto:
Accepted: 10.11.2000