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Numerično simuliranje delovanja hlajenih absorberjev s padajočim kapljevinskim filmom v navpični cevi

Numerical Simulation of the Performance of Cooled Absorbers with Falling Liquid Films in Vertical Tubes

MARTIN PFLÜGL

V članku je predstavljeno dejansko delovanje hlajenih in adiabatnih absorberjev za več primerov. Numerično simuliranje je izvedeno na podlagi matematičnega modela, ki popisuje sočasen prestop toplote in snovi v napravah s filmom kapljevine. Izračuni so predstavljeni v diagramih, ki prikazujejo delovanje absorberjev v odvisnosti od Reynoldsovega števila za film na vstopu raztopine v absorber in pogojev hlajenja. Obravnavana je tudi možnost zmanjšanja površine z uporabo obtoka bogate raztopine. © 1998 Strojniški vestnik. Vse pravice pridržane.

(Ključne besede: absorberji, delovanje absorberjev, simuliranje numerično, modeli matematični)

The real performance of cooled and adiabatic absorbers is demonstrated by several case studies. The cases were simulated numerically by a mathematical model for simultaneous heat and mass transfer of falling liquid film equipment. The calculated charts show the performance of absorbers depending on the entrance film Reynolds number and the cooling conditions. The possibility of exchange area savings of absorbers due to reflux of the rich solution is studied. © 1998 Journal of Mechanical Engineering. All rights reserved.

(Keywords: absorbers, performance of absorbers, numerical simulation, mathematical models)

0 UVOD

Pri termodinamičnem popisu ali simuliranju delovanja absorpcijske toplotne črpalke ali toplotnega transformatorja običajno naredimo precej poenostavitev. Pogosto predpostavimo, da je kapljevina, ki zapušča absorber v popolnem termodinamičnem ravnotežju s paro. Hkrati upoštevamo, da je absorber ustrezno izdelan in omogoča doseganje zahtevanih koncentracijskih razlik v raztopini. Da bi lahko ocenili pomen omenjene predpostavke, moramo preučiti dejansko obnašanje absorberja.

Absorberji in generatorji transformatorjev toplote imajo nalogo, da poleg temperaturnega dviga s prenosom snovi omogočijo prenos toplote. Obe nalogi je mogoče razdeliti tako, da v prvi napravi izvedemo samo prenos snovi, v drugi pa samo prenos toplote. Pri absorberjih je očitno, da je adiabatni absorber manj učinkovit od hlajenega. Če iz absorberja takoj ne odvajamo sproščene toplote s hladilnim sredstvom, se temperatura naglo dvigne in kmalu dosežemo točko nasičenja. Adiabatni absorberji lahko torej funkcionirajo samo v primeru, če je vstopajoča raztopina dovolj podhlajena.

V hlajenih absorberjih lahko omejimo temperaturo tako, da dosežemo najboljše razmerje med temperaturnim dvigom in zadostno izstopno koncentracijo v raztopini. Hlajeni absorberji torej delujejo učinkovito, če je vstopna raztopina blizu točke nasičenja. Zato so za toplotne črpalke primerni le absorberji s sočasnim odvodom toplote.

0 INTRODUCTION

For the thermodynamic design or simulation of an absorption heat pump or heat transformer cycle usually several simplifications are made. One of them is the assumption that the solution leaves the apparatus in the very state of thermodynamic vapour-liquid equilibrium. As a second one the apparatus is considered realizable for the requested solution field. To judge these assumptions the real behaviour of absorbers has to be examined.

Absorbers and generators for heat transformers, besides establishing the temperature boost by mass transfer, primarily have the task of exchanging heat. It is conceivable to split the two tasks so that in one apparatus the mass transfer is carried out and in a second one the heat exchange is made. But, considering e.g. the absorber, obviously the adiabatic absorber is less efficient than a cooled one. If the released heat of absorption is not removed immediately by a coolant the temperature of the absorbent increases rapidly and soon the saturation point is reached. Furthermore the adiabatic absorber functions only if the lean solution is fed sufficiently subcooled.

In the cooled absorber the increase of solution temperature can be restricted so that an optimum compromise is achieved between temperature boost and sufficient outlet concentration of the absorbate in the solution. Also the cooled absorber works well if the fed lean solution is around the saturation point. Therefore for heat pump applications only absorbers with simultaneous heat removal are suitable.

1 MATEMATIČNI MODEL

Za popis hlajenega absorberja je treba poleg ustreznega modela toka tekočine upoštevati še sočasen prenos toplote in snovi. Za tovrsten način popisa je primerna tehnika padajočega filma.

Za postavitev modela [1] smo izbrali dvodimenzionalni ustaljeni problem tankega filma kapljevine (raztopine soli), ki teče po ravni navpični steni (uporabimo lahko tudi za navpične cevi). Na površini filma poteka kondenzacija čiste pare hladiva in se ob sproščanju toplote absorbira v film. V filmu poteka prenos toplote in snovi, ki ustvarja temperaturne in koncentracijske poteke. Del sproščene toplote gre skozi celotno debelino filma in steno in ga odvajamo s hladilnim sredstvom. Preostali del toplote zviša temperaturo raztopine.

Ustrezne enačbe za popis problema dobimo z upoštevanjem ohranitvenih zakonov:

- ohranitev celotne mase,
- ohranitev mase laže hlapljive komponente,
- ohranitev gibalne količine in
- ohranitev toplotne energije.

Za poenostavitev, pri čemer ne naredimo bistvenih napak, smo izbrali naslednje predpostavke:

- Glavni tok filma v navpični smeri ima popolnoma razvit hitrostni potek $\varphi(\eta)$ na kateremkoli mestu v navpični smeri z.
- Hitrosti pare v plinski fazi so dovolj majhne, da lahko zanemarimo spremembo gibalne količine na meji faz.
- Fizikalne lastnosti filma kapljevine so konstantne skozi ves film za posamezno mesto v navpični smeri z.
- V smeri z je prenos toplote in snovi z molekularno difuzijo in turbulenco zanemarljiv v primerjavi s konvektivnim prenosom.

Z uporabo brezdimenzijskih veličin dobimo enačbo za hitrostni profil v navpični smeri $\varphi(\eta)$:

$$\left[1+\frac{\varepsilon_\tau(\eta)}{\nu}\right]\cdot\frac{d\varphi}{d\eta}-\frac{Re}{Fr}\cdot(1-\eta)=0 \qquad (1),$$

ki jo lahko rešimo ločeno, če izberemo ustrezen model turbulence. V brezdimenzijski obliki zapisa moramo upoštevati

$$\int_0^1 \varphi(\eta)\,d\eta=1 \qquad (2).$$

Iz enačbe (1) lahko ob podanem Reynoldsovem številu določimo Froudovo število. Zaradi spreminjanja masnega toka in lastnosti kapljevine, kot posledice spremembe temperatur in sestave, se rahlo spreminja tudi hitrostni potek v navpični smeri z.

Zaradi prenosa snovi skozi površino filma v samo eni smeri je potek prečnih hitrosti $\psi(\eta)$ podan z naslednjo enačbo:

1 MATHEMATICAL MODEL

In order to describe cooled absorbers, in addition to an adequate fluid flow model the simultaneous heat and mass transport has to be regarded. For this need the falling film technique is an excellent tool.

To establish the model [1] we consider the two-dimensional steady problem of a thin liquid film of salt solution flowing down a plane vertical wall (applicable also to vertical tubes). At the film surface pure vaporous absorbate condensates and becomes absorbed, accompanied by the release of heat. Mass and heat transport in the film takes place and leads to concentration and temperature profiles. One part of the transported heat passes all the liquid film, and the wall and is carried off by the coolant. The remaining part increases the solution temperature.

To get the governing equations for this problem the conservation laws have to be obeyed:

- conservation of total mass,
- conservation of the volatile component,
- conservation of momentum, and
- conservation of heat.

For simplification but not crucial restriction the following assumptions are made:

- The film mean flow in vertical direction has the fully developed velocity profile $\varphi(\eta)$ at any vertical position z.
- Vapour velocities in the gas phase are sufficiently low for interfacial momentum transfer to be neglected.
- The physical properties in the liquid film are considered constant across the film for one vertical position z.
- In z-direction compared to the convective transport the molecular and turbulent transport of mass and heat is neglected.

Introducing dimensionless quantities, the equation for the profile of vertical velocity $\varphi(\eta)$ is:

and can be solved independently if a suitable turbulence model is choosed. Thereby the standardization condition has to be taken into account

From equation (1) results the Froude number if the Reynolds number is given. Due to variyng mass flow rate and fluid properties controlled by temperature and concentration the vertical velocity profile is weakly dependent on the vertical z position.

Due to the unidirectional mass transport across the film surface the distribution of horizontal velocity $\psi(\eta)$ results from the following equation:

$$\psi(\eta)=\frac{d\delta}{dz}\cdot\eta\,\varphi(\eta)-\frac{m_a\,\delta}{M_f}\cdot\int_0^{\eta}\varphi(s)\,ds \qquad (3).$$

Za prenos toplote in snovi imamo sistem dveh parcialnih diferencialnih enačb:

For the mass and heat transport we get the system of two partial differential equations:

$$\varphi\frac{\partial x}{\partial\zeta}+\psi\frac{\partial x}{\partial\eta}=\frac{1}{Re}\frac{1}{Sc}\cdot\frac{\partial}{\partial\eta}\left[\left(1+\frac{\varepsilon_M}{D}\right)\frac{\partial x}{\partial\eta}\right] \qquad (4)$$

$$\varphi\frac{\partial T}{\partial\zeta}+\psi\frac{\partial T}{\partial\eta}=\frac{1}{Re}\frac{1}{\Pr}\cdot\frac{\partial}{\partial\eta}\left[\left(1+\frac{\varepsilon_Q}{a}\right)\frac{\partial T}{\partial\eta}+\frac{1}{c}\frac{\partial h}{\partial x}\cdot\left(1-\frac{1}{Le}+\frac{\varepsilon_Q-\varepsilon_M}{a}\right)\frac{\partial x}{\partial\eta}\right] \qquad (5).$$

Za rešitev tega sistema enačb je treba določiti še robne pogoje na mestu, kjer film raztopine vstopa v absorber, na površini stene in na površini filma:

In addition to this system of equations, the boundary conditions at the film entrance - at the wall and at the film surface one needs to consider:

$$\zeta=0 \quad , \quad 0\le\eta\le1: \qquad x=x_0 \qquad T=T_0 \qquad (6),$$

$\eta=0$: ohranitev snovi

$\eta=0$: conservation of mass

$$\left.\frac{\partial x}{\partial\eta}\right|_w=0 \qquad (7),$$

ohranitev toplote

conservation of heat

$$\alpha_c(\zeta)\cdot\left[T_w(\zeta)-T_c(\zeta)\right]=\frac{\lambda}{\delta}\left.\frac{\partial T}{\partial\eta}\right|_w \qquad (8),$$

$\eta=1$: ravnovesje faz

$\eta=1$: phase equilibrium

$$x_s(\zeta)=f\left(T_s(\zeta),p\right) \qquad (9),$$

ohranitev snovi

conservation of mass

$$m_a=x_s\,m_a+\frac{\rho\,D}{\delta}\left.\frac{\partial x}{\partial\eta}\right|_s \qquad (10),$$

ohranitev toplote

conservation of heat

$$m_a\left(\Delta h_a+h_{gg}-h_{gs}\right)+\alpha_g\left(T_g-T_s\right)=\frac{\lambda}{\delta}\left[\left.\frac{\partial T}{\partial\eta}\right|_s+\frac{1}{c}\left.\frac{\partial h}{\partial x}\right|_s\cdot\left(1-\frac{1}{Le}\right)\left.\frac{\partial x}{\partial\eta}\right|_s\right] \qquad (11).$$

Za robne pogoje (8), (10) in (11) velja, da ni turbulentnega prenosa snovi v neposredni bližini stene in na mejni površini med kapljevino in plinom.

Zaradi diferencialne razredčilne toplote v zadnjem členu enačbe (5) in robnih pogojev (9), (10) in (11) so enačbe (3), (4) in (5) povezane in jih je treba reševati hkrati. Turbulentni prenos gibalne količine, snovi in toplote je predstavljen s prenosnimi koeficienti ε_τ, ε_M in ε_Q. Za enoparametrsko obravnavo je izbran koncept mešalne dolžine. Po vzoru Grossmana [2] je film razdeljen na tri področja. V prvem področju, poleg stene je turbulentna viskoznost ε_τ izračunavana po priporočilu Van Driesta [3]. Za jedro turbulentnega toka je izbrana enačba, ki jo je predlagal Reichardt [4] in je modificirana za tok filma. Za popis turbulentne viskoznosti v bližini površine filma pa je izbran koncept, ki sta ga predlagala Lamourelle in Sandall [5] in predpostavlja zmanjšanje turbulence v bližini površine filma kot posledico površinske napetosti. Koncept uporablja posplošeno korelacijo, ki sta jo podala Mills in Chung [6].

For the boundary conditions (8), (10) and (11), the turbulent transport is considered to be damped out near the wall and the liquid/gas interface.

Due to the differential heat of solution in the last term of equation (5), and because of the boundary conditions (9), (10) and (11), the equations (3), (4) and (5) are coupled and can be solved only simultaneously. The turbulent transport of momentum, mass and heat is represented by the transport coefficients ε_τ, ε_M and ε_Q. For this 1-parameter approach the simple but adequate mixing length concept has been chosen. Following e.g. Grossman [2] the film is divided into three different regions. In the first region near the wall the turbulent viscosity ε_τ is calculated by a relation suggested by Van Driest [3]. For the turbulent core region the equation proposed by Reichardt [4] modified for the film flow is used. For the turbulent viscosity near the film surface we follow the concept of Lamourelle and Sandall [5], which supposes turbulence damping near the film surface by surface tension, and we use the generalized correlation of Mills and Chung [6].

Turbulentno difuzivnost za snov ε_M in toploto ε_Q je izbrana enako kakor za gibalno količino ε_τ. Uporaba predpostavk se ujema z izsledki Jischa [7] in Sin-Ming Yih-a [8], ki sta ugotovila, da sta turbulentno Prandtlovo in Schmidtovo število enaka 1 za Reynoldsova in Prandtlova števila, ki se pojavljajo pri reševanju problema padajočega filma.

Za rešitev sistema enačb (1) do (11) je bil razvit računalniški program in v zadnjem času bistveno izpopolnjen. Za izračun ravnovesja med paro in kapljevino, termodinamične in transportne lastnosti, sta bila izdelana dva sklopa podprogramov, in sicer za vodno raztopino litijevega bromida in glicerola.

2 OBRAVNAVANI PRIMER

Na delovanje absorberja vplivajo predvsem trije parametri:

- debelina filma δ oziroma masni pretok raztopine na enoto širine M_f oziroma Reynoldsovo število za film *Re*,
- koeficienta prenosa toplote hladiva α_c in
- temperaturna razlika med raztopino in hladilnim sredstvom $T_0 - T_c$.

Omenjeni parametri določajo količino prenesene toplote na hladilno sredstvo, povečanje koncentracije laže hlapljive komponente v kapljevitem absorpcijskem sredstvu in odmik od ravnovesnega stanja na izstopu iz absorberja. Odvisnosti smo prikazali v študiji absorberja v prvi stopnji dvostopenjskega toplotnega transformatorja.

Za absorpcijsko sredstvo je izbrana vodna raztopina litijevega bromida, v katerega se absorbira vodna para. Na sliki 1 so predstavljeni vsi pomembni

The turbulent diffusivities for mass ε_M and heat ε_Q are chosen here equal to that for momentum ε_τ. This follows the results of Jischa [7] and Siu-Ming Yih [8] who found the turbulent Prandtl and Schmidt numbers to be equal to 1 for the Reynolds and Prandtl number ranges to be considered for this falling film problem.

For the solution of the system of equations (1) to (11) a computer program had been developed in the past, and has recently been radically improved. To calculate the vapour/liquid equilibrium, thermophysical and transport properties, two subroutine packages for aqueous solutions of lithium bromide and glycerol have been supplied.

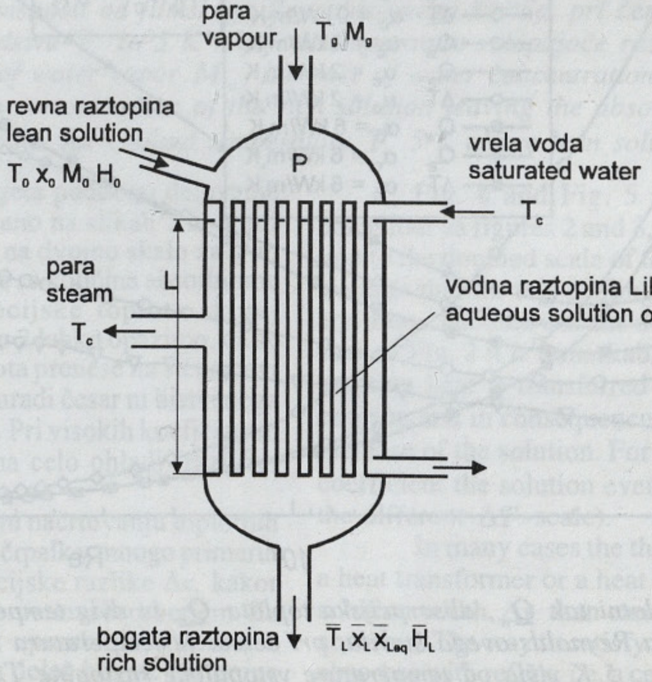
2 CASE STUDY

The performance of an absorber is characterized by the influence of mainly three parameters:

- the film thickness δ or the solution mass flow rate per unit horizontal length of exchange area M_f or the film Reynolds number *Re*,
- the heat transfer coefficient of the coolant α_c and
- the temperature difference between liquid solution and coolant $T_0 - T_c$.

These determine the amount of heat transferred to the cooling medium, the concentration increase of the volatile component in the liquid absorbent and the deviation from equilibrium at the absorber outlet. To demonstrate the dependencies a case study has been done for an absorber of the first stage of a two stage heat transformer.

An aqueous solution of lithium bromide was used as an absorbent for water vapour. In Fig. 1 all the base data for the simulation calculations are given.



Sl. 1. *Osnovni podatki za izračun primera absorberja s padajočim filmom*
Fig. 1. *Base data for the case study of a falling film absorber*

podatki za izračun simuliranja. V absorber dovajamo podhlajeno raztopino in na notranji strani navpičnih cevi ustvarimo film absorpcijskega sredstva. Na zunanji strani cevi je nasičena voda, ki se pri tem uparja. Zunanja stran absorberja pomeni uparjalnik za drugo stopnjo toplotnega transformatorja. Za prikaz na podlagi spreminjanja omenjenih treh parametrov je v diagramih prikazano delovanje absorberja, pri čemer je izbrana konstantna dolžina absorberja (2m).

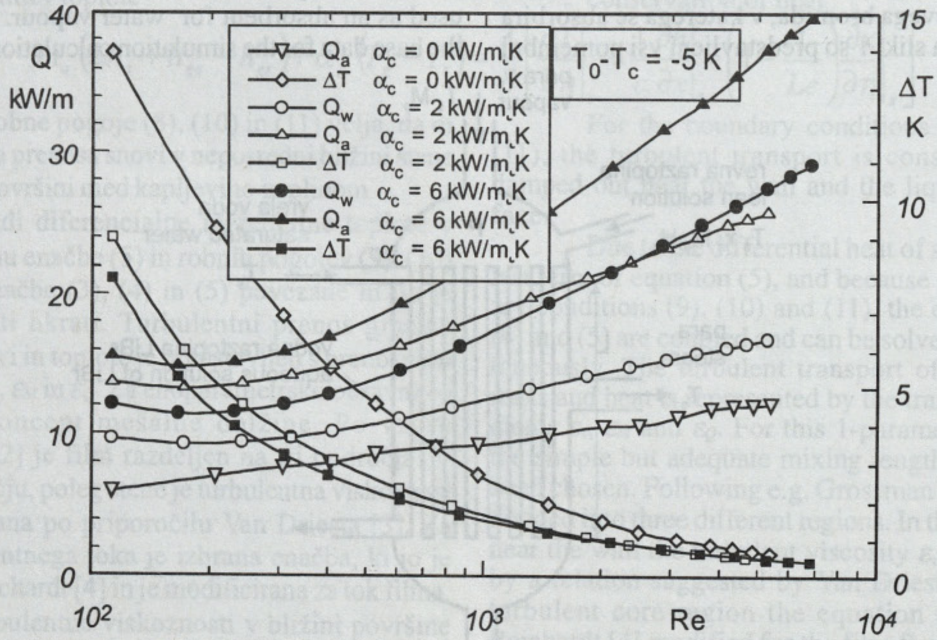
Na slikah 2 do 5 je predstavljeno delovanje absorberja za dva zanimiva primera. V prvem primeru absorber uparja vodo pri temperaturi T_c, ki je za 5 K nad vstopno temperaturo T_0 raztopine.

Slika 2 prikazuje, da se z zvečevanjem Reynoldsovega števila filma *Re* veča tako pri absorpciji sproščena toplota Q_a, kakor tudi toplota, ki se prek stene cevi prenese na hladilno sredstvo (hladivo) Q_w in ga uparja. Pojav je še posebej izrazit v območju visokih *Re*. Dvig temperature raztopine na izstopu se zmanjšuje z naraščajočim *Re* številom. Ugotovimo lahko tudi, da se s povečevanjem koeficienta prestopa toplote na strani hladilnega sredstva α_c povečujeta tudi Q_a in Q_w in da je na vodo, ki jo uparjamo, prenesen le del toplote. Za primerjavo smo izbrali adiabatni absorber. Pri adiabatnem absorberju ni prenosa toplote na hladilno sredstvo. Sproščena absorpcijska toplota je bistveno nižja kakor pa v primeru hlajenja in se kaže v dvigu temperature filma raztopine. Dvig temperature je zato bistveno večji kakor v primeru hlajenja. Visok dvig temperature pri adiabatnem absorberju zmanjšuje razliko koncentracij, ki je gonilna sila za prenos snovi med površino in jedrom filma.

The subcooled lean solution is fed to the vertical tubes establishing the falling film on the inner wall. Outside the tubes saturated water is vaporized so forming the evaporator of the second stage of the heat transformer. To design the performance charts the above three parameters have been varied for a constant absorber length of 2 m.

To demonstrate the behaviour of an absorber two instructive examples out of the results of several simulation calculations are given in Figs. 2 to 5. In the first case the absorber is able to evaporate water with a bubble temperature of T_c 5 K above the entrance temperature T_0 of the lean solution.

Fig. 2 shows that both the absorption - released heat Q_a and the heat Q_w transferred to the wall - and therefore to the coolant to produce vapor - increase with the film Reynolds number *Re*, especially in the higher *Re* range. The temperature rise of the solution, however, decreases with the increasing *Re* number. We note also that Q_a and Q_w increase with increasing heat transfer coefficient of the coolant α_c, and that only a part of the absorption heat is transferred to the evaporating water. For comparison, the case of an adiabatic absorber is also included. Clearly there is no transferred heat and the absorption heat is considerably lower than that of the cooled cases, but all of them contribute to the temperature rise of the film. Therefore this temperature increase is substantially higher than that for the cooled cases. This high temperature rise of an adiabatic absorber decreases the driving concentration difference between the film surface and the core of the film.

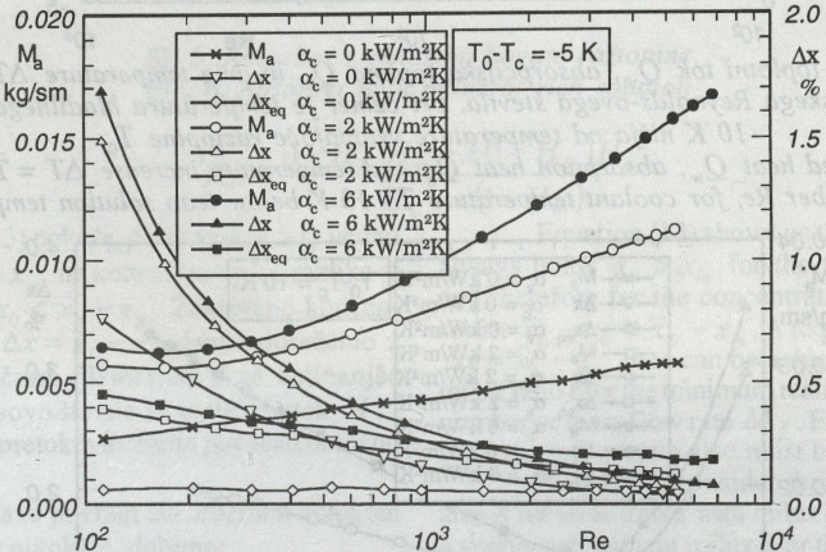


Sl. 2. *Preneseni toplotni tok* Q_w, *absorpcijska toplota* Q_a *in dvig temperature* $\Delta T = \overline{T}_L - T_0$ *v odvisnosti od filmskega Reynolds-ovega števila, pri čemer je temperatura hladilnega sredstva* T_c *za 5 K višja od temperature vstopajoče raztopine* T_0

Fig. 2. *Transferred heat* Q_w, *absorption heat* Q_a *and temperature increase* $\Delta T = \overline{T}_L - T_0$ *vs. film Reynolds number Re, for coolant temperature* T_c *5 K above lean solution temperature* T_0

Na sliki 3 vidimo, da se z zvečevanjem Reynoldsovega števila in koeficienta prenosa toplote α_c zvečuje tudi masni tok absorbirane vodne pare M_a. Z večanjem debeline filma se zmanjšuje koncentracijska razlika Δx in tudi razlika Δx_{eq} med ravnovesno koncentracijo $\overline{x}_{Leq}$ za povprečno izstopno temperaturo $\overline{T}_L$ in povprečno izstopno koncentracijo $\overline{x}_L$. Iz tega lahko povzamemo, da absorber vedno zapušča podhlajena raztopina. Prav tako kakor M_a se tudi Δx in Δx_{eq} zvečujeta s povečanim koeficientom prestopa toplote α_c. Pri adiabatnem absorberju ($\alpha_c = 0$) ni moč doseči tako velikih koncentracijskih razlik Δx kakor v primeru hlajenja. Hlajeni absorber je zato bolj učinkovit od adiabatnega.

In Fig. 3 it is seen that also the absorbed mass of water vapour M_a increases with the increasing Reynolds number and increasing heat transfer coefficient α_c. The thicker the film is, however, the smaller will be the concentration span between inlet and outlet Δx and the difference Δx_{eq} between equilibrium concentration $\overline{x}_{Leq}$ for the mean outlet temperature $\overline{T}_L$ and the mean outlet concentration $\overline{x}_L$. Moreover this means that the rich solution leaves the absorber subcooled in all cases. Like M_a also Δx and Δx_{eq} increases with the coolant heat transfer coefficient. For an adiabatic absorber ($\alpha_c = 0$) the reachable solution width Δx is less than that for the cooled case. Evidently the cooled absorber will be more efficient than the adiabatic one.



Sl. 3. *Absorbirani masni tok vodne pare, povišanje masnega deleža vode (hladiva) v raztopini* $\Delta x = x_0 - \overline{x}_L$ *in odmik od ravnovesne sestave s hladivom bogate raztopine, ki zapušča absorber* $\Delta x_{eq} = \overline{x}_{Leq} - \overline{x}_L$ *v odvisnosti od filmskega Reynolds-ovega števila, pri čemer je temperatura hladilnega sredstva* T_c *za 5 K višja od temperature vstopajoče raztopine* T_0

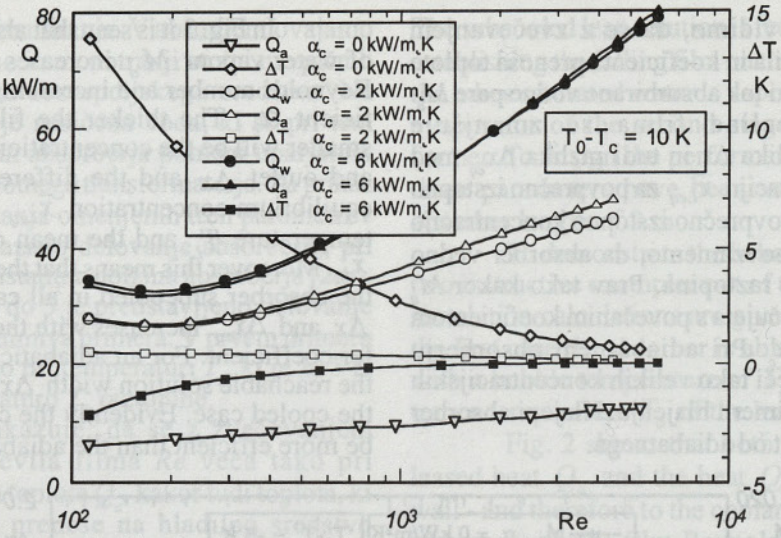
Fig. 3. *Absorbed mass of water vapor* M_a*, increase of water concentration* $\Delta x = x_0 - \overline{x}_L$ *and deviation from equilibrium concentration of the rich solution leaving the absorber* $\Delta x_{eq} = \overline{x}_{Leq} - \overline{x}_L$ *vs. film Reynolds number Re, for coolant temperature* T_c *5 K above lean solution temperature* T_0

Sliki 4 in 5 prikazujeta podobno delovanje absorberjev, kakor je prikazano na slikah 2 in 3, pri čemer pa moramo opozoriti na dvojno skalo za Q in M_a. V primeru odvoda toplote se količina absorbirane pare in sproščene absorpcijske toplote skoraj podvojita. V nasprotju s sliko 2 lahko opazimo, da se skoraj vsa absorpcijska toplota prenese na steno cevi oziroma hladilno sredstvo, zaradi česar ni bistvenega dviga temperature raztopine. Pri visokih koeficientih prestopa toplote se raztopina celo ohladi (različno merilo za ΔT).

Pri termodinamičnem načrtovanju toplotnih transformatorjev in toplotnih črpalk v mnogo primerih zahtevamo večje koncentracijske razlike Δx, kakor pa jih lahko dosežemo s preprostim absorberjem. Za zadovoljitev takšnih zahtev uporabimo absorber z obtokom, pri čemer določen delež bogate raztopine vračamo nazaj v absorber (sl. 6). Z mešanjem izstopajoče in vstopajoče raztopine se spremenijo

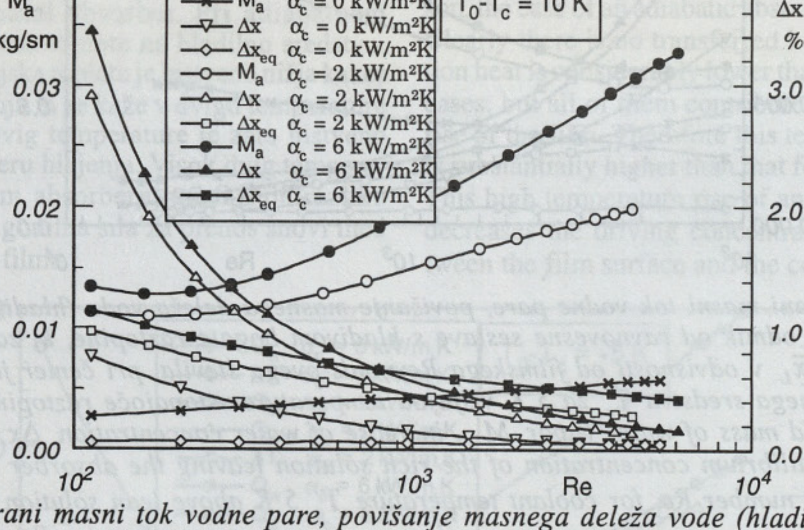
Fig. 4 and Fig. 5 show nearly the same behaviour as figures 2 and 3, but one must pay attention to the doubled scale of the Q- and M_a-axes. So we note that for this cooling case the absorbed heat and mass become almost doubled, too. Unlike the case of Fig. 2 it is remarkable that nearly all the absorption heat is transferred to the wall, say to the coolant, and in consequence there is no temperature increase of the solution. For the higher heat transfer coefficient the solution even becomes cooled (note the different ΔT-scale).

In many cases the thermodynamic design of a heat transformer or a heat pump requires a higher solution width Δx than can be realized by a simple absorber. The way to satisfy this demand is to use an absorber with reflux, i.e. a certain amount of the rich solution is fed back into the absorber (see Fig. 6). By mixing the reflux stream to the inlet stream the ab-



Sl.4. *Preneseni toplotni tok Q_w, absorpcijska toplota Q_a in dvig temperature $\Delta T = \overline{T}_L - T_0$ v odvisnosti od filmskega Reynolds-ovega števila, pri čemer je temperatura hladilnega sredstva T_c za 10 K nižja od temperature vstopajoče raztopine T_0*

Fig. 4. *Transferred heat Q_w, absorption heat Q_a and temperature increase $\Delta T = \overline{T}_L - T_0$ vs. film Reynolds number Re, for coolant temperature T_c 10 K below lean solution temperature T_0*



Sl. 5. *Absorbirani masni tok vodne pare, povišanje masnega deleža vode (hladiva) v raztopini $\Delta x = x_0 - \overline{x}_L$ in odmik od ravnovesne sestave s hladivom bogate raztopine, ki zapušča absorber $\Delta x_{eq} = \overline{x}_{Leq} - \overline{x}_L$ v odvisnosti od filmskega Reynolds-ovega števila, pri čemer je temperatura hladilnega sredstva T_c za 10 K nižja od temperature vstopajoče raztopine T_0*

Fig. 5. *Absorbed mass of water vapor M_a, increase of water concentration $\Delta x = x_0 - \overline{x}_L$ and deviation from equilibrium concentration of the rich solution leaving the absorber $\Delta x_{eq} = \overline{x}_{Leq} - \overline{x}_L$ vs. film Reynolds number Re, for coolant temperature T_c 10 K below lean solution temperature T_0*

parametri, ki popisujejo dotok raztopine. Z uvedbo obtočnega razmerja:

sorber feed variables of state become changed. With the definition for the reflux ratio:

$$r = \frac{M_r}{M_{out}} \tag{12}$$

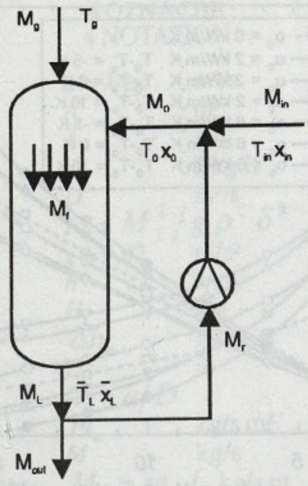
izračunamo sestavo pri vstopu v absorber:

we get for the feed concentration:

$$x_0 = \frac{\left(1 - \overline{x}_L\right) x_{in} + r\left(1 - x_{in}\right) \overline{x}_L}{1 - \overline{x}_L + r\left(1 - x_{in}\right)} \tag{13}$$

in entalpijo pri vstopu, ki določa temperaturo vstopa v absorber T_0:

and for the enthalpy at the absorber feed which determines the feed temperature T_0:



Sl. 6. *Absorber z obtokom bogate raztopine*
Fig. 6. *Absorber with reflux of rich solution*

$$H_0 = \frac{\left(1-\overline{H}_L\right)H_{in} + r\left(1-H_{in}\right)\overline{H}_L}{1-\overline{H}_L + r\left(1-H_{in}\right)} \tag{14}$$

Enačba (13) pokaže, da za vsak $r > 0$ vedno velja, da je $x_0 > x_{in}$ in koncentracijska razlika v absorberju $\bar{x}_L - x_0 < \bar{x}_L - x_{in}$. Zahtevano koncentracijsko razliko $\Delta x = \bar{x}_L - x_{in}$ lahko dosežemo z najmanjšim obtočnim razmerjem r za najmanjše mogoče Reynoldsovo število ali masni pretok M_f. Pri večjih masnih pretokih moramo povečati obtočno razmerje.

S primerjavo površin absorberja z obtokom A in površine brez obtoka A_0 dobimo:

Equation (13) shows us that for $r > 0$, there always holds $x_0 > x_{in}$ for the feed concentration, and therefore for the concentration span in the absorber $\bar{x}_L - x_0 < \bar{x}_L - x_{in}$. A required solution width $\Delta x = \bar{x}_L - x_{in}$ then can be achieved by a minimum reflux ratio r for the minimum realizable film Reynolds number or mass flow rate M_f. For higher mass flow rates the reflux ratio also must be increased.

Now let us consider the absorber exchange area A for an absorber with reflux compared to A_0 for a simple one without reflux. For the area ratio we get:

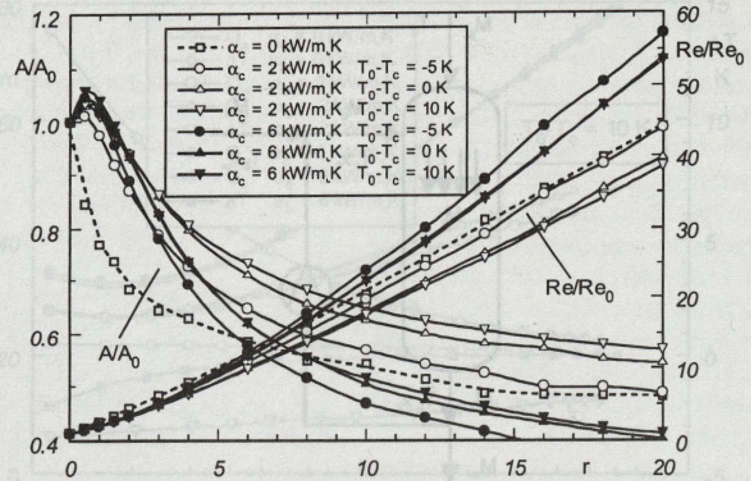
$$\frac{A}{A_0} = \left(1 + r\frac{1-x_{in}}{1-\bar{x}_L}\right) \cdot \frac{M_f\big|_{r=0}}{M_f} \cdot \frac{L}{L\big|_{r=0}} \tag{15}$$

Pri konstantnih robnih pogojih za absorber (pretoki, temperature in sestave pri vstopu in izstopu) lahko spreminjamo obtočno razmerje. S tem izračunamo površino in dolžino (višino) absorberja za poljuben obtok, ki je večji od najmanjšega pri različnih kombinacijah masnega toka M_f (ali Reynoldsovega števila za film *Re*).

S spreminjanjem obtočnega razmerja med 0 in 20, pri konstantni dolžini absorberja (2 m) lahko prikažemo vpliv obtočnega razmerja na površino absorberja. Na sliki 7 lahko vidimo, da s povečanjem obtočnega razmerja lahko celo zmanjšamo površino ne glede na način odvoda toplote. Vzrok je v tem, da se s povečevanjem obtočnega razmerja močno poveča tudi Reynolds-ovo število za film, kar vodi k večji količini na cev prenesene toplote Q_w na enoto širine, kar je vidno tudi na slikah 2 in 4. Zaradi zmanjšanja površine bi pričakovali, da se bo pri absorberju z obtokom zmanjšala tudi količina toplote, prenesena na hladilno sredstvo. Na sliki 8 lahko vidimo, da je največje zmanjšanje Q_c med 6 in 16% v različnih razmerah hlajenja in za največje obtočno razmerje.

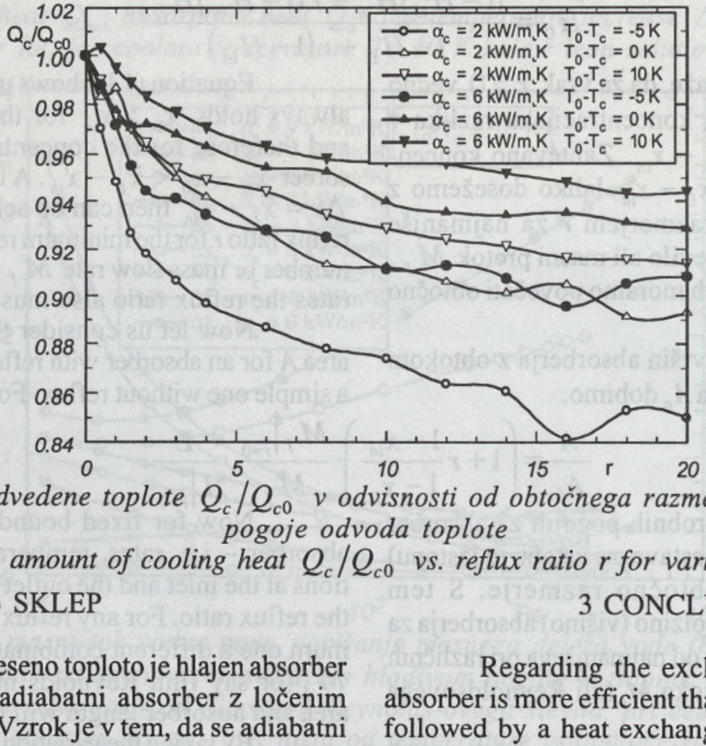
Now for fixed boundary conditions of the absorber – i.e. rates, temperatures and concentrations at the inlet and the outlet – it is possible to vary the reflux ratio. For any reflux greater than the minimum one a different combination of mass flow rate M_f (or say film Reynolds number *Re*), exchange area and absorber length will be obtained.

By taking the variation of the reflux ratio from 0 up to 20, and fixing the length to 2 m the dependence of exchange area ratio can be calculated. Fig. 7 shows that for reflux ratios greater than about 2 and for all cooling conditions even a saving of exchange area can be achieved. This is due to the fact that for great reflux ratios the film Reynolds number also increases substantially. This leads to greater heat transfer Q_w per unit horizontal length of exchange area, as it is clearly seen in Figs. 2 and 4. Due to the area saving it is to be expected that the total heat amount Q_c transferred to the coolant will be lower for an absorber with reflux. For this reason let us inspect Fig. 8 noting that the maximum decrease of Q_c according to the various cooling conditions and the maximum reflux ratio lies between about 6 and 16 %.



Sl. 7. *Razmerje površin* A/A_0 *in Reynolds-ovih števil za film* Re/Re_0 *v odvisnosti od obtočnega razmerja r in za različne pogoje odvoda toplote*

Fig. 7. *Ratio of absorber exchange area* A/A_0 *and film Reynolds number* Re/Re_0 *vs. reflux ratio r for various cooling conditions*



Sl. 8. *Razmerje odvedene toplote* Q_c/Q_{c0} *v odvisnosti od obtočnega razmerja r in za različne pogoje odvoda toplote*

Fig. 8. *Ratio of total amount of cooling heat* Q_c/Q_{c0} *vs. reflux ratio r for various cooling conditions*

3 SKLEP

Glede na preneseno toploto je hlajen absorber bolj učinkovit kakor adiabatni absorber z ločenim prenosnikom toplote. Vzrok je v tem, da se adiabatni absorber zaradi intenzivnega porasta temperature hitro približa ravnovesnemu stanju. Hlajeni absorberji lahko tudi pri večjih masnih pretokih odvajajo razmeroma velike količine toplote na hladilno sredstvo in absorbirajo večje količine pare. Po drugi strani pa so za večje spremembe koncentracij primerne predvsem izvedbe s tankim filmom kapljevine. Iz nasprotujočih si teh dveh trditev sklepamo, da je treba narediti kompromis med koncentracijsko razliko in količino odvedene toplote.

Absorber z obtokom bogate raztopine lahko zagotovi velike razlike koncentracij laže hlapljive komponente v raztopini. Pri večjih obtočnih razmerjih lahko celo zmanjšamo površino absorberja, pri čemer je zmanjšanje celotne, na hladilno sredstvo prenesene količine toplote zanemarljivo.

3 CONCLUSION

Regarding the exchanged heat the cooled absorber is more efficient than the adiabatic absorber followed by a heat exchanger. This is because the adiabatic absorber, due to the strong temperature increase in the solution, soon reaches a near equilibrium state. Also a cooled absorber with a rather high mass flow can transfer a greater amount of heat to the coolant and absorb more vapour. On the other hand a wide solution field is only realized when designing for thin liquid films. These last two contrasting statements must lead to a compromise when designing an simple absorber for required solution width and heat transfer.

The absorber with reflux of the rich solution can provide still greater concentration spans of the volatile component in the solution. For a greater reflux ratio even a saving of exchange area can be obtained. The decrease of total heat transferred to the coolant attached thereto remains insignificant.

4 OZNAČBE
4 NOTATION

temperaturna prevodnost raztopine	$a = \lambda / \rho c$	m²/s	thermal diffusivity of solution
površina absorberja	A	m²	exchange area
površina absorberja brez obtoka	A_0	m²	exchange area of absorber without reflux
specifična toplota raztopine	c	J/kg K	heat capacity of solution
difuzivnost v raztopini	D	m²/s	diffusion coefficient in solution
Froudovo število	$Fr = M_f^2 / g \rho^2 \delta^3$		Froude number
zemeljski pospešek	$g = 9{,}92$	m/s²	gravity
entalpija	h	J/kg	enthalpy
tok entalpije	H	J/s	enthalpy stream
absorpcijska toplota	Δh_a	J/kg	heat of absorption
dolžina absorberja	L	m	absorber length
Lewisovo število	$Le = a/D$		Lewis number
gostota masnega toka absorbirane pare	m_a	kg/s m²	flux of absorbed mass
masni tok	M	kg/s	rate of mass flow
masni tok absorbirane pare na dolžinsko enoto	$M_a = m_a L$	kg/s m	rate of absorbed mass
masni tok filma raztopine na dolžinsko enoto	M_f	kg/s m	film mass flow rate
masni pretok v absorber vračajoče se raztopine	M_r	kg/s	rate of reflux mass flow
tlak	p	bar	pressure
Prandtlovo število	$Pr = \nu / a$		Prandtl number
absorpcijska toplota na dolžinsko enoto	Q_a	W/m	rate of absorption heat
na hladilno sredstvo prenesen toplotni tok	Q_c	W	rate of total coolant heating
na hladilno sredstvo prenesen toplotni tok brez upoštevanja obtoka	Q_{c0}	W	rate of total coolant heating without reflux
na hladilno sredstvo prenesen toplotni tok na dolžinsko enoto	Q_w	W/m	rate of heat transferred to coolant
razmerje obtokov	r		reflux ratio
Reynoldsovo število	$Re = M_f / \rho \nu$		Reynolds number
Schmidtovo število	$Sc = \nu / D$		Schmidt number
temperatura filma raztopine	T	K	film temperature
dvig temperature raztopine	$\Delta T = T_0 - \bar{T}_L$	K	solution temperature increase
hitrost filma v navpični smeri	u	m/s	vertical film flow velocity
hitrost filma v prečni smeri	υ	m/s	transverse velocity in the film
masno razmerje hladiva v raztopini	x	wt%	concentration of absorbate in solution
povišanje masnega razmerja hladiva	$\Delta x = \bar{x}_L - x_0$	wt%	absorbate concentration increase
razlika masnega razmerja do ravnovesnega stanja	$\Delta x_{eq} = x_{Leq} - \bar{x}_L$	wt%	deviation from equilibrium concentration
razdalja od stene v vodoravni smeri	y	m	horizontal distance from wall in film
razdalja od vstopa filma v navpični smeri	z	m	vertical distance from top of film
koeficient prenosa toplote	α	W/m² K	heat transfer coefficient
debelina filma	δ	m	film thickness
turbulentna snovska difuzivnost	ε_M	m²/s	turbulent mass diffusivity
turbulentna toplotna difuzivnost	ε_Q	m²/s	turbulent heat diffusivity
difuzivnost vrtincev	ε_τ	m²/s	eddy diffusivity
brezdimenzijska oddaljenost od stene	$\eta = y/\delta$		dimensionless distance from wall
toplotna prevodnost raztopine	λ	W/m K	thermal conductivity of solution
kinematična viskoznost raztopine	ν	m²/s	kinematic viscosity of solution
gostota raztopine	ρ	kg/m³	density of solution
brezdimenzijska hitrost filma v smeri toka	$\varphi = u/\bar{u}$		dimensionless film flow velocity
brezdimenzijska hitrost filma prečno na smer toka	$\psi = \upsilon/\bar{u}$		dimensionless transverse velocity
brezdimenzijska razdalja v navpični smeri	$\zeta = z/\delta$		dimensional vertical distance
Indeksi			*Subscripts*
hladilno sredstvo	c		coolant
ravnovesje	eq		equilibrium
plinska faza	g		gas phase
vstop v absorber z upoštevanjem obtoka	in		input in absorber with reflux
dno absorberja	L		bottom of absorber
izstop iz absorberja z upoštevanjem obtoka	out		output from absorber with reflux
površina filma	s		surface of film
stena	w		wall
vrh absorberja	0		top of absorber

Eksponent		*Superscript*
povprečna vrednost v filmu na mestu v navpični smeri	$\bar{\ }$	mean value in film at vertical position z

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