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Termohidravlična analiza obratovanja uparjalnika za ukapljeni naftni plin

A Thermohydraulic Analysis of a Liquefied-Petroleum-Gas Revaporizer

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Prispevek obravnava analizo obratovanja električnega uparjalnika za ukapljeni naftni plin. Na začetku je podan opis naprave in delovanje v ustaljenih obratovalnih razmerah. Nato je definiran cilj analize in vpeljan navidez osnosimetrični prerez uparjalnika. Podane so vodilne enačbe toka newtonske tekočine v območju sekundarne kapljevine za prenos toplote in toka skozi porozni grelnik. Definirani so robni pogoji na mejah računskega območja. Ločeno so podane osnovne kriterialne enačbe za vrednotenje prenosnih pojavov v posameznih delih uparjalnika. Poseben poudarek je namenjen razmeram konvektivnega uparjanja binarne zmesi v cevni vijačni spirali. Opisan je iterativni računski postopek, s katerim je doseženo končno obratovalno stanje naprave. Na koncu so predstavljeni dobljeni rezultati s komentarjem in sklepi. Za izbrane parametre je obratovalna točka uparjalnika znotraj predpisanih temperaturnih mej.

(Ključne besede: prenos toplote, uparjalniki, analize termohidravlične, plini naftni ukapljeni)

This paper deals with the thermohydraulic characteristics of an electrical liquefied-petroleum-gas (LPG) revaporizer. To begin with both the revaporizer's description and its working performances are presented. The main goals of the analysis are defined and the quasi-axisymmetrical revaporizer section is introduced. The governing equations for Newtonian fluid flow in the region of the secondary liquid and for flow through a porous heater are presented. The boundary conditions on the computational region boundaries are prescribed. Further, basic empirical corelations for the evaluation of the transport phenomena within the individual revaporizer zones are presented. Special attention is devoted to the convective boiling process of the binary mixture in helically coiled tubes. The iterative calculating procedure with which we finally reached the working state of the device is explained. At the end the achieved results are discussed with comments and conclusions included. The operating point of the revaporizer was to lie inside the prescribed temperature range for the selected combination of process parameters.

(Keywords: heat transfer, vaporizers, thermohydraulic analysis, liquified petroleum gas)

0 UVOD

Ukapljeni naftni plin (UNP) se uporablja kot natančnejše ime za nekaj vrst ogljikovodikov, kakor so propan (C_3H_8), butan (C_4H_{10}) in zmesi propana in butana v različnih sestavinskih razmerjih. UNP je na temperaturi okolice in pri atmosferskem tlaku v plinastem agregatnem stanju in se v tej obliki uporablja kot vir energije oz. gorivo. Že pri manjših nadtlakih ob nespremenjeni temperaturi (nekaj barov – odvisno od deleža sestavnih komponent) UNP preide v kapljevito agregatno stanje in se v tej obliki preprosto prevaža in skladišči.

Odvisno od potreb po UNP-u se ta porabnikom v večini primerov dostavlja v prenosnih jeklenkah, hramih ali cisternah. V vseh hranilnikih je največji del polnitve v kapljevitem agregatnem stanju, le manjši del nad gladino zaseda plinasta faza. Pri polnjenju hranilnikov je takšno prostorninsko

0 INTRODUCTION

Liquefied petroleum gas (LPG) is the name used for several kinds of hydrocarbons, such as propane (C_3H_8), butane (C_4H_{10}) and various propane-butane mixtures. At atmospheric pressure and room temperature LPG has a liquid aggregate state, and in this state it is used as an energy source. At lower gauge pressures (a few bar – depending on the component contents) and temperatures LPG can be easily converted into a liquid aggregate state. This is an important characteristic of LPG, and is used for its economic transport.

With regards to requirements, LPG is normally delivered to consumers in gas bottles, containers and cisterns. In all types of storage most of the volume is occupied by the liquid phase, and only a small part above the liquid surface is filled by the gas phas. The appropriate volume ratio between the phases during razmerje med fazama odvisno od visoke vrednosti prostorninskega temperaturnega raztezka kapljevite faze UNP-a [15].

Odvzem plinaste faze neposredno iz shrambnega prostora, ki ga pogosto imenujemo *naravno uparjanje* UNP-a je povezan s celo vrsto pomanjkljivosti (majhni masni pretoki, uparjanje po frakcijah, usedanje težjih primesi, nevarnost podhladitve UNP-a pri večjih odvzemih). Tem pomanjkljivostim se lahko izognemo z uvedbo *prisilnega oz. pospešenega uparjanja*, ki temelji na odvzemu kapljevite faze UNP-a iz skladiščnih prostorov. Sprememba agregatnega stanja UNP-a v tem primeru poteka zunaj plinskih hranilnikov, v zato posebej skonstruiranih uparjalnikih, ki jih kot dodatne komponente uvajamo v plinska omrežja.

Uparjalniki UNP-a so posebno skonstruirani dvofazni prenosniki toplote, ki izrabljajo toplotno energijo določenih zunanjih virov za pospešeno uparjanje UNP-a. Najbolj uveljavljena razdelitev uparjalnikov za UNP je glede na vir toplote, ki ga ti uporabljajo za pospešeno uparjanje UNP-a. Tako poznamo električne uparjalnike, uparjalnike z vodno paro, toplovodne uparjalnike ter uparjalnike, ki izkoriščajo vrele ostanke zgorevanja UNP-a [17]. V središču pozornosti pričujočega prispevka je električni uparjalnik za UNP s posredno kapljevino za prenos toplote.

1OPIS IN DELOVANJE UPARJALNIKA

Uparjalnik (slika 1) ima obliko pokončne valjaste posode [18], [19], ki jo sestavljajo valjni plašč (1) ter pokrov (2) in dno plašča (3). Na pokrovu posode sta dovodni (4) (sl. 2) in odvodni cevovod (5) ter spremljajoča krmilna in varnostna oprema. Znotraj posode uparjalnika je navpično nameščen cevni snop, ki se prilega obliki plašča in je na svojih koncih povezan z vstopnim (6) oz. izstopnim (7) priključkom na pokrovu uparjalnika. Cevni snop sestoji iz dveh sosrednih in simetričnih vijačnih cevnih spiral, zunanje (8) in notranje (9). Cevni snop dodatno sestavljajo še trije navpično nameščeni pomožni cevni vodniki (10, 11 in 12).

Skozi ustrezno odprtino je v notranjost plašča v smeri njegove navpične osi vstavljen električni grelnik (13) nespremenljive moči in je pritrjen za dno posode. Uporovni električni grelnik sestavljajo grelna telesa U, obdana z zaščitnim plaščem, ki so pritrjena na skupno krožno nosilo grelnika (14). Na pokrovu uparjalnika so po njegovem obodu pritrjeni trije tovarniško zapečateni kapilarni termostati (15a, 15b in 15c) s pasivnimi stikali, industrijski živosrebrni termometer (16) in mehanski merilnik ravni sekundarne kapljevine za prenos toplote (17). V središču pokrova je nameščen še avtomatski merilnik ravni (električno ravensko stikalo) sekundarne kapljevine v plašču uparjalnika (18). Vsi omenjeni instrumenti s svojimi

reservoir loading is a consequence of the high-temperature dilatation coefficient of the LPG's liquid phase [15].

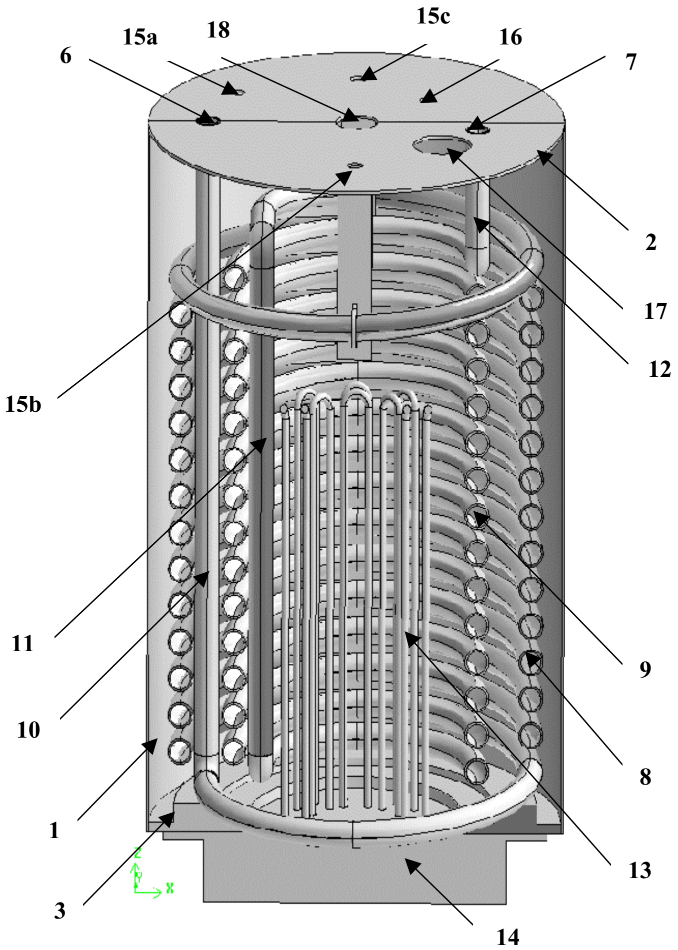
Gas-phase discharging directly from a gasholder, which is often referred to as *natural LPG revaporization*, is accompanied by some imperfections (low mass-flow rate, fractional vaporisation, heavy fractions sedimentation, a risk of bottle subcooling at high discharging rates). To avoid these problems *forced or promoted vaporisation* is frequently used. In this case the LPG's liquid phase is taken out directly from the gas reservoir and the phase transition occurs outside gasholder in specially designed evaporators, which are introduced into the gas network as additional system components.

LPG revaporizers are two-phase heat exchangers that use heat energy from some external sources to promote the evaporation of LPG. The best known classification of LPG revaporizers is in terms of the heat source to be used for the forced revaporization of the LPG. There are electrical revaporizers, revaporizers with hot water or water steam as the heat source, and revaporizers that use the hot combustion products of LPG [17]. This article deals with an electrical LPG revaporizer with a secondary liquid for the heat transfer.

1 DESCRIPTION OF THE REVAPORIZER AND ITS WORKING CHARACTERISTICS

The revaporizer (Figure 1), which is designed as a vertical cylindrical vessel, consists of a cylindrical shell (1), a cover (2) and a vessel bottom (3). On the cover there are supply (4) (Figure 2) and discharging (5) pipelines and auxiliary control and safety equipment. Within the vessel there is a vertically placed tube bundle. At its terminations the tube bundle is connected with inlet (6) and outlet (7) connections on the revaporizer cover. The tube bundle consists of two concentric and symmetric helically coiled tubes, outer (8) and inner (9). The tube bundle also includes three vertically placed auxiliary connecting tubes (10, 11 and 12).

Through a suitable opening in the vessel bottom in the direction of the vertical axis a constant-power electrical heater is inserted (13). The electrical resistance heater consists of heating U-elements covered with copper sheaths and linked together with a circular heater holder (14). On the revaporizer cover three capillary thermostats (15a, 15b and 15c) with passive contactors, an industrial mercury thermometer (16) and a mechanical secondary-liquid-level gauge (17) are mounted. In addition, in the centre of the revaporizer cover, an automatic secondary-liquid-level gauge (18) is installed. The sensors of all this equipment are immersed in the



Sl.1. *Prikaz notranjosti uparjalnika z osnosimetričnim prerezom cevnega snopa in grelnika*
Fig. 1. *Revaporizer interior and axisymmetric sections of the tube bundle and heater*

tipali segajo v notranjost posode (sl. 9) in so do določene globine potopljeni v sekundarno kapljevino za prenos toplote.

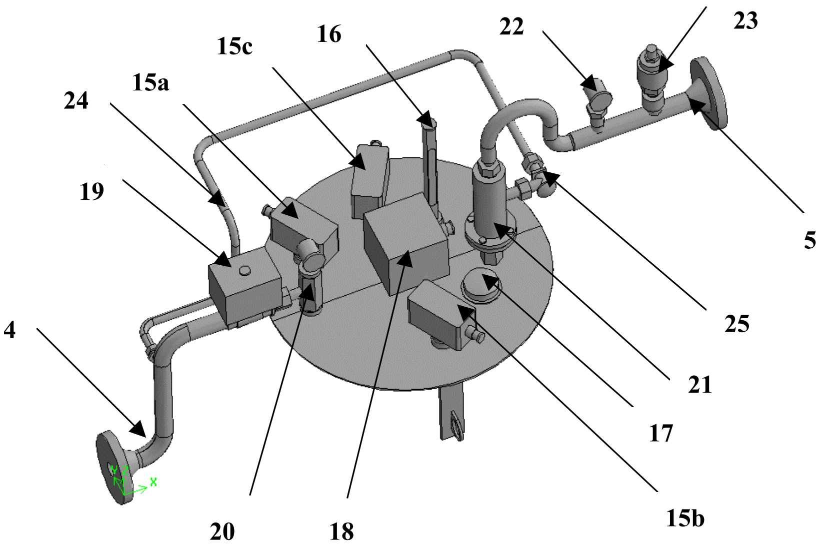
Pred vstopnim priključkom sta na dovodni cevovod (4) pritrjena elektromagnetni ventil (19) in manometer vstopne strani (20). Za izstopnim priključkom so na odvodnem cevovodu (5) nameščeni glavni zaporni ventil (21), manometer izstopne strani (22) ter tlačni varnostni ventil (23). Dovodni (4) in odvodni cevovod (5) uparjalnika sta povezana z zunanjo povratno cevjo (24), ki ima na mestu prehoda v glavni zaporni ventil (21) pritrjen dodatni zaporni ventil za plinske napeljave (25). Zunanja povratna cev (24) in zaporni ventil (25) sta namenjena odpravljanju posledic poplavljanja cevnega snopa (nezgodne razmere [18] in [19]). V posodo je do določene višine nad cevnim snopom nalita sekundarna kapljevina za prenos toplote (transformatorsko olje ali raztopina monoetilenglikola in vode).

Dovodni cevovod uparjalnika je priklopljen na hranilnik UNP-a. Hranilniki za UNP so običajno izdelani iz jeklene pločevine brez toplotne izolacije in je UNP, ki je v njih, v termodinamičnem ravnotežju z okolico [15]. Odvodni cevovod uparjalnika je povezan s porabnikom plina oz. gorilnikom, pred katerim je krmilnik tlaka oz. krmilnik pretoka [16].

secondary liquid for heat transfer in the revaporizer vessel.

In front of the inlet connection, an electromagnetic valve (19) and an inlet side manometer (20) are mounted on the supply pipeline (4). Behind the outlet connection, the main block valve (21), the outlet side manometer (22), and the pressure safety valve (23) are assembled on the discharging pipeline (5). The supply (4) and discharging (5) pipelines are additionally connected together by the external recurrent tube (24). On recurrent tube at the joint situ with main block valve (21), additional block gas valve is mounted (25). External recurrent tube (24) and block valve (25) serve as auxiliary system for elimination of tube bundle flooding consequences (incident circumstances [18] and [19]). Up to the prescribed level over the tube bundle, revaporizer vessel is filled up with secondary liquid for heat transfer (mineral oil or solution of mono-ethylene-glycol and water).

The supply pipeline of the revaporizer is connected to the LPG reservoir. They are usually manufactured from steel plate without heat insulation, and the LPG within the reservoir is in thermodynamic equilibrium with the surroundings [15]. On the opposite side, the discharging pipeline of the revaporizer is connected with the gas consumer. Normally, it is a burner. In front of the burner a pressure or mass-flow rate regulator is placed [16].



Sl.2. *Pokrov uparjalnika s krmilno in varnostno opremo*
Fig. 2. *Revaporizer cover with control and safety equipment*

Parna faza, ki je nad prosto gladino v shrambni posodi za UNP, potiska kapljevito fazo po navpični sifonski cevi skozi izstopni ventil hranilnika v dovodni cevovod (4) električnega uparjalnika. Po vklopu električnega grelnika (13), zaradi naravne konvekcije v sekundarni kapljevini in predvsem zaradi slabega odvoda toplote (ni pretoka UNP-a skozi cevni snop, ker je elektromagnetni ventil (19) na začetku zaprt), slednja akumulira sproščeno toplotno energijo grelnika in se hitro segreva. Ko temperatura kapljevine v točki namestitve tipala termostata, ki krmili delovanje elektromagnetnega ventila (15a), doseže temperaturo 65 ^{o}C se elektromagnetni ventil (19) odpre in v cevni snop priteče kapljevita faza UNP-a. Ker kapljevita faza, ki priteka iz hranilnika, ustreza točki na vrelni krivulji UNP-a ob podanem sistemskem tlaku, se uparjanje začne takoj po vstopu kapljevite faze v uparjalnik.

V primeru, da temperatura sekundarne kapljevine v točki namestitve tipala termostata, ki krmili delovanje električnega grelnika (15c), doseže temperaturo 80 ^{o}C, se grelnik (13) avtomatsko izklopi. Na pokrovu uparjalnika je nameščen tretji termostat (15b), ki je namenjen za krmiljenje električnega grelnika, in sicer v primeru, da iz določenih razlogov prvi termostat (15a) odpove, njegov električni stik pa je sklenjen pod 85 ^{o}C. Med temperaturama merilnih točk 65 ^{o}C in 80(85) ^{o}C je delovno območje uparjalnika. V tem temperaturnem območju uparjalnik deluje ustaljeno, morebitna sprememba parametrov postopka (poglavje 2) pa lahko povzroči premik delovne točke iz ene v drugo lego.

2 DEFINICIJA PROBLEMA

Prispevek sega na področje konstruiranja dvofaznih prenosnikov toplote. Izvirna konstrukcijska

Due to the pressure head the gas phase in the LPG gasholder pushes the liquid phase out through a vertical siphon tube and the outlet valve to the supply pipeline (4) of the electrical revaporizer. After the electrical heater (13) start-up, the free convection and the low-heat transfer rate (LPG does not flow through the tube bundle because at the start the electromagnetic valve (19) is closed) cause the secondary liquid to accumulate the heat energy of the heater and warm up very fast. When liquid temperature at the point where the thermostat sensor for the electromagnetic valve control is placed reaches 65 ^{o}C the valve is opened and the liquid phase of the LPG starts to flow into the tube bundle. Due to fact that the state of the liquid phase entering the tube bundle corresponds to the dew point of LPG for the defined system pressure the evaporation starts immediately after liquid phase enters the revaporizer.

In the case when the secondary liquid temperature at the point where the thermostat sensor for the electric heater working control is placed reaches 80 ^{o}C, the electric heaters (13) are automatically turned off. On the revaporizer cover the third thermostat (15b) is placed. It also serves for electrical heater control in case the first thermostat breaks down. It is switched on at 85 ^{o}C. As a result the operating region of the revaporizer has to be found between the temperatures measured by the two control thermostat sensors. These temperatures are 65 and 80(85) ^{o}C. In this temperature region the revaporizer operates normally and steady-state conditions are usually achieved. Changes to the process parameters governing the revaporizer's thermohydraulic behaviour (Chapter 2) may cause the operating point to be moved to another position.

2 PROBLEM DEFINITION

This paper deals with heat excanger that have a two-phase-flow design. The original construction izvedba električnega uparjalnika je razvita v podjetju Nafta Lendava d.o.o. (*konstruiranje na novo*), na kar so sledile postopne izkustvene spremembe sedanjih izvedb (*optimizacija*). Po več ko dveh desetletjih so razvili izvedbo, za katero smo z namenom nadaljnjih izboljšav izvedli numerično analizo obratovanja, ki jo podajamo v pričujočem prispevku. Sedanji električni uparjalnik za UNP je namenjen obratovanju v širokem območju parametrov postopka. Temperatura okolice (T_{sur}), sestava plinske zmesi ($\xi_{C_3H_8}$), zračni tokovi okrog uparjalnika (v_w), vrsta sekundarnega sredstva in višina, do katere ta sega s svojo prosto gladino (H_{sl}) (sl. 3b), ter masni pretok UNP-a ($\dot{m}_{UNP}$), so veličine postopka, ki definirajo obratovalne značilnosti uparjalnika. Večina prenosnikov toplote je namenjena delovanju pri točno določeni kombinaciji parametrov postopka, pri čemer so dovoljena le manjša odstopanja od predpisane delovne točke. V tukaj podanem primeru se parametri postopka lahko močno spreminjajo, uparjalnik pa mora nemoteno delovati v čim širšem območju spreminjajočih se vplivnih veličin (*delovanje v novih razmerah*). Mogoče je torej veliko število obratovalnih točk, ki skupaj dajejo obratovalni diagram uparjalnika. Izdelava obratovalnega diagrama uparjalnika za UNP je končni cilj raziskave. Glede na dejstvo, da obstaja zelo veliko število kombinacij parametrov postopka, ki določajo delovno točko uparjalnika, smo se v prispevku omejili na eno samo delovno točko oz. na eno izbrano kombinacijo parametrov postopka (preglednica 1). Razviti algoritem je mogoče uporabiti za določitev celotnega delovnega območja obravnavanega uparjalnika.

Namen je ugotoviti, ali uparjalnik ob izbrani kombinaciji parametrov postopka deluje in koliko daleč je tako definirana delovna točka od meje neobratovanja. Če so temperature sekundarne kapljevine v točkah namestitve tipal krmilnih termostatov v predpisanem območju (60 do 85 °C), potem uparjalnik nemoteno deluje. Namen smo dosegli tako, da smo s postopnim spreminjanjem robnih pogojev na mejah računskega območja izpolnili delne (uparjanje, pregretje in izgube v okolico) in s tem celotno toplotno bilanco uparjalnika. Preverili smo velikost grelne površine sedanjega cevnega snopa za dosego predpisanih izhodnih veličin pregrete parne faze UNP-a. Parametri postopka, ki

of the electrical LPG revaporizer was developed by Nafta Lendava d.o.o. (*new design*). Some empirical modifications to the existing construction followed (*optimization*). After more than two decades a new construction has been developed for which, with the aim of additional improvements, we performed a numerical analysis of the working conditions presented in this contribution. The existing LPG revaporizer is designed to work within a wide region of process parameters. The surrounding temperature (T_{sur}), the gas-mixture composition ($\xi_{C_3H_8}$), the air flow around the revaporizer (v_w), the secondary liquid type and its filling level in the revaporizer vessel (H_{sl}), and the mass-flow rate of the LPG ($\dot{m}_{UNP}$) are the process parameters that define the operating conditions of the revaporizer. The vast majority of heat exchangers are designed to work for an exactly defined combination of process parameters. Usually, only small deviations from the defined working point are allowed. In the case analysed here the process parameters change significantly and the revaporizer must operate without interruption in as wide as possible region of the affecting parameters (*working under the conditions of the new process parameters*). A large number of operating points defines the revaporizer's operational diagram. The development of an LPG revaporizer operational diagram is the final goal of this analysis. Due to the fact that there are many combinations of process parameters defining the revaporizer's operational points, we limited ourselves to one selected combination of process parameters (Table 1.) The developed algorithm may then be used to determine the entire working region of the revaporizer.

The main goal of our research was to find out whether the revaporizer works for a chosen combination of process parameters, and how far away from the limits of the working region is the defined working point. If the temperatures of the secondary liquid at the control thermostat sensor points are in the prescribed range (60-85 °C), the revaporizer works without interruption. The goal can be reached with a numerical analysis by changing the boundary conditions on the boundary of computational domain and by satisfying the partial (evaporation, superheating and heat loses to surroundings) and the global heat balances of the revaporizer. The size of the tube bundle's surface available for heat transfer was controlled at the

Preglednica 1. *Parametri postopka delovnega stanja, za katero je izveden nadzor obratovanja uparjalnika*
Table 1. The p*rocess parameters defining the working state of the revaporizer for which the numerical analysis is performed*

parametri postopka process parameters					
$T_{sur}\left[{}^{o}C\right]$	$\xi_{C_3H_8}[\%]$	$\dot{m}_{LPG}[kg/h]$	$v_w[m/s]$	sekundarna kapljevina secondary liquid	$H_{sl}[m]$
+ 20,0	0,6	$1,0\cdot\dot{m}_{LPG,opt}$	10,0	transformatorsko olje mineral oil	$H_{sl,max}$

definirajo izbrano delovno točko, so podani v preglednici 1.

V uparjalniku potekajo postopki odvisnega prenosa toplote: (a) naravna konvekcija sekundarne kapljevine v posodi uparjalnika, (b) dvofazni (konvektivno uparjanje) in enofazni (pregretje parne faze) diabatni tok UNP-a skozi vijačni cevni snop ter (c) prenos toplote v okolico (toplotne izgube). Zapletena geometrijska oblika cevnega snopa ter notranja zanka naravne konvekcije v plašču uparjalnika ne omogočata izrabe uveljavljenih metod in izkustvenih izrazov za termohidravlični preračun preprostejših izvedb uparjalnikov [24]. Uporaba metod računalniške dinamike tekočin omogoča zanesljivo vrednotenje poteka naravne konvekcije v plašču ([5] in [7]). Po drugi strani te metode za zdaj še ne dajejo zadovoljivih rezultatov na področju numerične simulacije konvektivnega uparjanja pri gospodarskih industrijskih napravah ([5] in [10]). Na pokrovu uparjalnika so krmilni instrumenti, katerih merilne veličine je mogoče uporabiti za spremljanje integralnih kazalnikov obratovanja uparjalnika. Kombinacija uveljavljenih izkustvenih zvez, računalniška dinamika tekočin in fizikalne meritve (krmilni instrumenti na pokrovu uparjalnika) zagotavljajo želene rezultate.

3 NUMERIČNI MODEL

Poskusi s 3D numeričnim modelom uparjalnika so pokazali, da je ta način prezahteven, tako z vidika velikosti problema kakor tudi zaradi svoje zapletenosti in potrebe po velikem številu poenostavitev. Računalniški program FIDAP 8.5, s katerim smo izvedli izračune, ne omogoča modeliranja pojavov, ki nastopajo pri spremembi agregatnega stanja v sistemu kapljevina – para [7]. Popolno uparjanje zmesi propana in butana, ki poteka od vrednosti masnega deleža parne faze 0 do vrednosti 1, prehaja skozi vse načine dvofaznega toka ([3] in [20]) (od mehurčastega prek obročastega do disperzno-kapljičastega) in je izredno zahtevno za numerično modeliranje. Zato smo vpeljali *navidez osnosimetrični* prerez uparjalnika (sl. 3). V nadaljevanju utemeljujemo vpeljavo te poenostavitve:

(a) Problem naravne konvekcije v posodi uparjalnika s sredinsko nameščenim grelnikom je osnosimetričen, torej so učinki obodnega deleža toka zanemarljivi.
(b) Vpliv »plazečih tokov«, ki se pojavljajo vzdolž vijačnih lokov cevnega snopa, je zaradi lokalnega pomena slednjih in njihove nizke intenzitete zanemarljiv.
(c) Odseki pomožnih povezovalnih cevi so zelo kratki v primerjavi z razvito dolžino cevnega snopa in bistveno ne vplivajo na termohidravlično dogajanje v plašču uparjalnika (kolena in podobni odmiki od enoličnosti pretočne poti – sl. 1 – poz.

prescribed outlet temperature of the superheated LPG gas phase. The process parameters defining the selected working point are presented in Table 1.

Within the revaporizer, conjugate heat-transfer processes occur: (a) natural convection of the secondary liquid in the revaporizer vessel, (b) two-phase (convective boiling) and single-phase (superheating of the gas phase) non-adiabatic LPG flow through the helically formed tube bundle and (c) heat transfer to the surroundings (heat loses). The complex geometry of the tube bundle and the internal loop of natural convection in the revaporizer vessel do not allow the use of well-established methods and empirical correlations for the thermohydraulic analysis for a simple design of the evaporators. The methods of computational fluid dynamics enable a reliable evaluation of the natural covection in the shell ([5] and [7]). However, these methods have so far not given satisfactory results in the area of the numerical simulation of convective boiling processes in industrial vaporisers ([5] and [10]). On the revaporizer cover there are control instruments that may be used to give us values of the integral working parameters. Therefore, the combination of known empirical corelations, computational fluid dynamics and measurements (control instrument on the revaporizer cover) is used to obtain the desired results.

3 NUMERICAL MODEL

The modelling work on the construction of a 3D numerical model of the revaporizer showed the complexity of the 3D approach and the need for many simplifications in order to obtain results. The FIDAP 8.5 program package was used to solve the governing equations of fluid flow. Physical phenomena occurring during the phase transformation in the liquid–gas system could not be modelled by the program capabilities [7]. The total evaporation of the propane–butane mixtures, ranging from vapour quality 0 to 1, passes through all the regimes of the two-phase flow ([3] and [20]) (from bubbly, through annular, to the dispersed-flow regime) and is very complex for the numerical modelling. These reasons led us to the introduction of a quasi-axisymmetric section of the revaporizer (Figure 3). Explanations for these simplifications are given below:

(a) The natural convection phenomenon in the revaporizer vessel with the heater in its central part may be considered as an axisymmetrical one as the effects of the tangential velocity component can be neglected.
(b) The creeping flows occurring along the tube bends are only important on a local scale because of its low intensity. Therefore, we can also neglect its influence on the flow field.
(c) The length of the auxiliary connecting tubes is very short compared with the total length of the tube bundle, and its effect on the thermohydraulic conditions of the revaporizer is not important (bends and similar curved flow paths (Figure 1 –

10, 11 in 12) imajo lahko pomemben vpliv na režim dvofaznega toka v področju uparjanja [6]).

(d) Pojavi mehurčastega vrenja in konvektivnega izparevanja, ki potekajo v dvojni vijačni cevni spirali, so zaradi majhnih vrednosti sistemskih parametrov $(p, \dot{q}, G)$ in nizke intenzitete sredobežnih sil razširjeni vzdolž večjega dela cevnega snopa. Zato je mogoče dvofazni tokovni režim v področju uparjanja, ki poteka vzdolž posameznega cevnega loka, preslikati v en sam pripadajoči mu krožni prerez v osnosimetrijski ravnini. Enaka analogija velja v področju pregretja parne faze UNP-a.

(e) Nagib cevnih lokov je zelo majhen in ga z vpeljavo osnosimetričnega modela zanemarimo. S tem so spiralni cevni loki nadomeščeni z dvema vrstama sosrednjih zvitkov.

(f) Zračni prostor nad gladino pomeni dodaten upor toplotnim izgubam v okolico. Vpliv naravne konvekcije v tem delu posode smo v tej fazi dela zanemarili. Ta poenostavitev ni imela bistvenega vpliva na rezultat izračuna.

(g) Električni grelnik je stisnjene izvedbe (velika površina za prenos toplote na enoto prostornine) in ga je mogoče numerično modelirati s porozno snovjo z ustrezno predpisanimi snovnimi lastnostmi (poroznost in prepustnost).

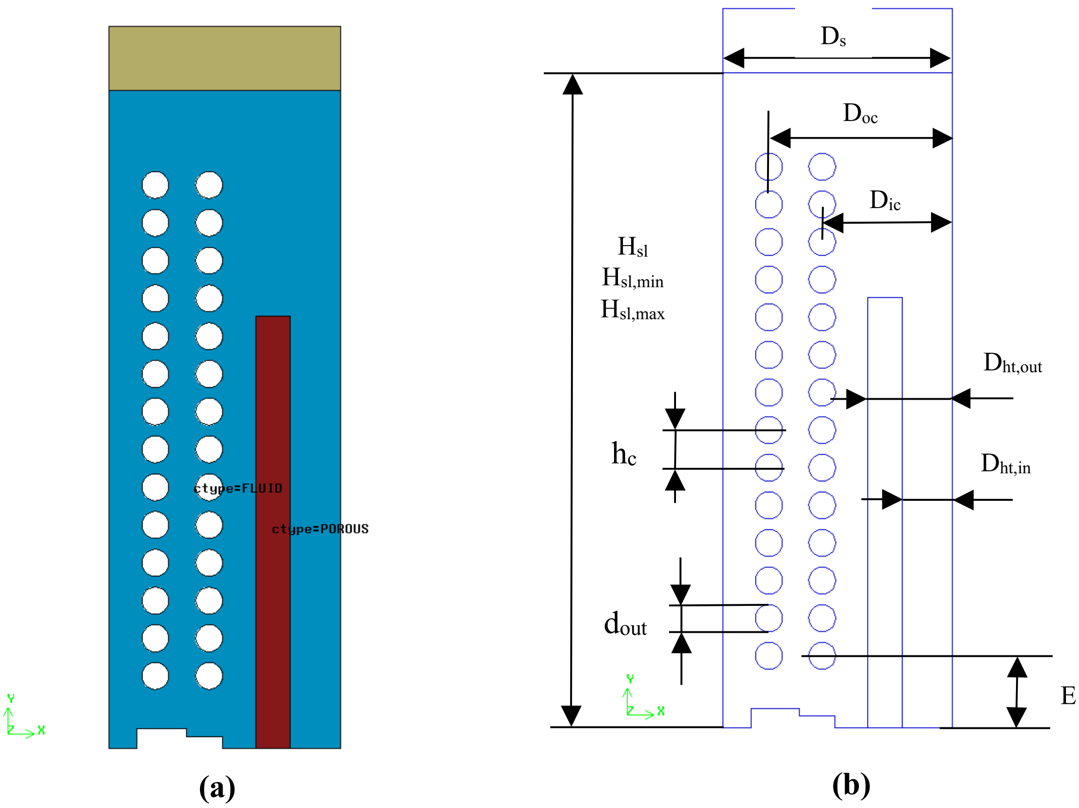
pos. 10, 11 and 12) but may play an important role in the two-phase flow regime when convective boiling occurs [6]).

(d) Because of the low values of the system parameters $(p, \dot{q}, G)$ and low centrifugal forces, the processes of bubbly boiling flow and convective evaporation are spread over a large part of the tube bundle. Because of this, the two-phase flow regime that occurs within one tube turn could be represented by a corresponding circular section in the axisymmetric plane. The same analogy is valid in the region of superheating of the LPG gas phase.

(e) The slope of the tube turn has a very low value and can be neglected when the axisymmetrical section is introduced. Thus, helically coiled turns in the 3D presentation are substituted by two rows of concentric rings.

(f) The air space above the free surface represents an additional thermal factor. Natural convection in this part of the vessel was neglected as its impact on heat loses was assumed to be negligible.

(g) The electrical heater has a compact form (large heat-transfer surface per unit volume) and can be numerically modelled as a heated porous region with suitably selected physical and transport properties (porosity and permeability).



Sl.3. *Navidez osnosimetrični prerez uparjalnika: (a) področji reševanja vodilnih enačb toka, (b) geometrijske veličine prereza*

Fig. 3. *Quasi-axisymmetrical section of revaporizer: (a) regions where governing equations are solved, (b) geometrical dimensions*

4 VODILNE ENAČBE

Numerična simulacija tokovnih in toplotnih razmer je izvedena za področje naravne konvekcije sekundarne kapljevine v uparjalniku. Naravno konvekcijo v zračnem prostoru nad prosto gladino smo zanemarili. Področje sekundarne kapljevine je razdeljeno na področje naravne konvekcije in področje toka skozi porozni grelnik. V nadaljevanju so podane vodilne enačbe za področje toka v sekundarni kapljevini in poroznem grelniku [7].

4.1 Naravna konvekcija v plašču uparjalnika

Splošna oblika zakona ohranitve mase se glasi:

4 GOVERNING EQUATION

The numerical calculation of the velocity and temperature fields is performed in the region of natural convection of the secondary liquid in the revaporizer shell and in the region of the porous heater. The natural convection within the air space over the free surface was neglected. The governing equations describing the physics of the problem can be written separately for natural convection in a pure fluid and for flow in a porous region [7].

4.1 Natural convection in the revaporizer vessel

The general form of the continuity equation is written as:

$$\frac{\partial \rho}{\partial t}+\left(\rho u_i\right)_{,i}=0 \qquad (1),$$

kjer sta ρ gostota, u_i pa vektor hitrosti. Ohranitev gibalne količine, pri kateri je upoštevan Boussinesqueov približek temperaturne spremenljivosti gostote le pri masnih silah, je podana z enačbo:

where ρ is the fluid density and u_i is the velocity vector. The momentum equation with Boussinesq's approximation, where the temperature's influence on the fluid mass density is considered only within the body force term, is written as:

$$\rho_0\left(\frac{\partial u_i}{\partial t}+u_j u_{i,j}\right)=-p_{,i}+\left[\mu\left(u_{i,j}+u_{j,i}\right)\right]_{,j}+\left(\rho-\rho_0\right)g_i \qquad (2).$$

V enačbi (2) so ρ_0 gostota pri primerljivi temperaturi T_0, p termodinamični tlak, μ dinamična viskoznost in g_i težnostni pospešek. Ob tem velja povezava $\left(\rho-\rho_0\right)/\rho_0=-\beta_T\left(T-T_0\right)$, ki pomeni normalizirano funkcijsko odvisnost gostote od temperature. Z β_T je označen prostorninski temperaturni raztezek. Energijska enačba za temperaturo kot neodvisno spremenljivko se glasi:

In equation (2), ρ_0 represents the fluid density at the reference temperature T_0, p is the thermodynamic pressure, μ is the dynamic viscosity and g_i is the gravity vector. The term $\left(\rho-\rho_0\right)/\rho_0=-\beta_T\left(T-T_0\right)$ represents a normalized density temperature variation function, where β_T is the thermal volume expansion coefficient. The energy equation with temperature as an independent variable is written as:

$$\rho c_p\left(\frac{\partial T}{\partial t}+u_i T_{,i}\right)=\left(\lambda T_{,i}\right)_{,i}+I \qquad (3),$$

kjer so c_p specifična izobarna toplota, T temperatura, λ toplotna prevodnost in I intenziteta toplotnega vira oz. ponora.

where c_p is sthe pecific isobaric heat, T stands for the temperature, λ is the heat conductivity and I is the heat source.

4.2 Tok sekundarne kapljevine skozi porozni grelnik

Zakon ohranitve mase je podan z enačbo (1). Zakon ohranitve gibalne količine se glasi [7]:

4.2 Secondary liquid flow through the porous region

The continuity equation is presented with expression (1). The momentum equation for the porous region can be written as [7]:

$$\frac{\rho}{\phi}\frac{\partial u_i}{\partial t}+\left(\frac{\rho\varpi}{\sqrt{\kappa_i}}\left\|u_i\right\|+\frac{\mu}{\kappa_i}\right)u_i=-p_{,i}+\left[\bar{\mu}(u_{i,j}+u_{j,i})\right]_{,j}+\rho g_i \qquad (4),$$

kjer so ϕ poroznost, ϖ koeficient vztrajnosti, κ_i prepustnost porozne snovi, $\|u\|$ absolutna vrednost hitrostnega vektorja in $\bar{\mu}$ dejanska dinamična viskoznost. Energijsko enačbo zapišemo v obliki:

where ϕ is the porosity, ϖ is the inertia coefficient, κ_i is the permeability of the porous matter, $\|u\|$ is the magnitude of the velocity and $\bar{\mu}$ is an effective dynamics viscosity. The energy equation is written as:

$$\left(\rho c_p\right)_e\frac{\partial T}{\partial t}+\rho c_p u_j T_{,j}=\left(\lambda_e T_{,j}\right)_{,j}+I \qquad (5),$$

kjer indeks e velja za primerjalne lastnosti, ki

where subscript e indicates an effective property whose povezujejo posamezne lastnosti tekočine in trdne faze, in so predpisane z naslednjimi izrazi: $(\rho c_p)_e = \phi \rho c_p + (1-\phi)(\rho c_p)_s$ in $\lambda_e = \phi\lambda + (1-\phi)\lambda_s$. V teh izrazih se indeks s nanaša na lastnosti trdnine, lastnosti brez indeksa pa veljajo za kapljevino. Zgoraj podani sistem enačb predstavlja znani Forchheimer-Brinkmanov model porozne snovi.

value needs to be prescribed on the basis of the average properties of the liquid and solid phases. These properties are defined by the next expressions: $(\rho c_p)_e = \phi \rho c_p + (1-\phi)(\rho c_p)_s$ and $\lambda_e = \phi\lambda + (1-\phi)\lambda_s$. Here, the subscript s refers to solid matrix properties, and the properties without subscripts are those of the liquid phase. The equation system presented above is sometimes referred to as the Forchheimer-Brinkman model.

5 ROBNI POGOJI

5 BOUNDARY CONDITIONS

V nadaljevanju so podani robni pogoji na mejah računskega območja Ω navidezno osnosimetričnega prereza uparjalnika. Predpisani so hitrostni in toplotni robni pogoji. Hitrostni robni pogoj podamo v naslednji splošni obliki

The boundary conditions on the boundaries of the computational domain Ω of the quasi-axisymmetrical revaporizer section are presented. The velocity and hea-transfer boundary conditions are prescribed. The velocity boundary conditions are written as:

$$u_i = u_i(l,t) \qquad (6),$$

kjer je l koordinatna razdalja vzdolž ustreznega roba. Vzdolž vseh robov so vrednosti hitrostnega vektorja nič. Na simetrijski osi je normalna komponenta hitrosti nič, medtem ko je vzdolž simetrijske osi predpisan pogoj »proste« vrednosti vzdolžne komponente hitrosti [7]. Mešani (Cauchyjev) toplotni robni pogoj se glasi:

where l is the coordinate distance along the appropriate boundary. The zero-velocity boundary condition is prescribed along all the solid boundaries. On the symmetry axis of the revaporizer the free-slip boundary condition is set. The momentum flux has to be zero in the direction normal to the symmetry axis [7]. The general form of the mixed boundary condition is given by the expression:

$$\dot{q} = \alpha(T - T_{ref}) \qquad (7),$$

kjer so $\dot{q}$ gostota toplotnega toka, α toplotna prestopnost in T_{ref} temperatura okolice. Mešani robni pogoji so predpisani vzdolž dna, plašča in pokrova uparjalnika ter v področju konvektivnega uparjanja in pregretja parne faze UNP-a (cevni loki). Za vsak izmed teh robov določimo vrednost toplotne prestopnosti in vrednost primerljive temperature. Neumannov robni pogoj (gostota toplotnega toka) se glasi:

where $\dot{q}$ is the heat flux, α is the convective heat-transfer coefficient and T_{ref} is a reference temperature (surroundings temperature). The mixed (Cauchy) boundary conditions for heat transfer are prescribed along all the boundaries of the computational domain. These boundaries are the bottom, the shell, the revaporizer cover and the circular sections of the helical tube where the convective boiling and superheating of the LPG take place. The Neumann boundary condition (constant heat flux):

$$\dot{q} = konst \qquad (8),$$

in je predpisan vzdolž robov poroznega grelnika.

is prescribed along the boundaries of the porous heater.

5.1 Toplotni robni pogoji

5.1 Temperature boundary conditions

Na robovih računskega območja predpišemo prilagojeno toplotno prestopnost, s katero upoštevamo tudi prevod toplote skozi trdne stene. Pri vijačnih spiralnih ceveh je opazna določena trajna deformacija prečnega prereza, ki je posledica postopka izdelave. Neenakomernost debeline cevne stene zato vpliva na značilnosti prevoda toplote skozi steno cevi. Jensen [9] je podal analitično rešitev tega problema. V našem primeru smo ta vpliv zanemarili in upoštevali dejansko debelino cevne stene pred izdelavo (imenska debelina). Prilagojeno toplotno prestopnost določimo s splošno veljavnim izrazom,

On the boundaries of the computational domain a modified heat-transfer coefficient way prescribed. In this way the heat conduction through the solid walls of the computational region was also taken into consideration. As result of the manufacturing process the helically coiled tubes have some permanent deformation of the transverse section. Accordingly, the non-uniformity of tube-wall thickness affects the heat transfer through the tube walls. Jensen [9] presented an analytical solution of this problem. Here, we have neglected this effect and taken the actual tube-wall thickness before the manufacturing process. Thus, the next expression ki se glasi:

for the modified heat-transfer coefficient is obtained:

$$\alpha^* = 1/\left(R + 1/\alpha\right) \tag{9}$$

kjer je R upor prevoda toplote. Vrednost upora prevoda toplote je določena z izrazom $R = \delta/\lambda$ za ravno steno (dno in pokrov plašča) in z izrazom $R = 1/(2\pi\lambda)\cdot\ln\left(d_{out}/d_{in}\right)$ za krožno steno (plašč, cev cevnega snopa). Z δ je označena debelina prevodne stene, z d_{out} zunanji in z d_{in} notranji premer krožne stene. Za vsako izmed področij določimo vrednost toplotne prestopnosti, izrazi, ki veljajo za vsako izmed teh področij pa so podani v nadaljnjih oddelkih. Temperaturni robni pogoj v območju obtekanja posode zapišemo z enakostjo:

where R represents the heat conduction resistance. The heat conduction resistance is defined by the expression $R = \delta/\lambda$ for the plain wall (bottom and revaporizer cover) and by the expression $R = 1/(2\pi\lambda)\cdot\ln\left(d_{out}/d_{in}\right)$ for the circular wall (revaporizer shell, tubes of tube bundle). The δ stands for the thickness of the conducting walls, d_{out} is the outer and d_{in} the inner diameter of the circular wall. The temperature boundary condition in the region of the air flow around the revaporizer shell is written as

$$T_{ref} = T_{sur} \tag{10}$$

kjer je T_{sur} temperatura okolice (preglednica 1). V primeru uparjanja dvokomponentne zmesi UNP-a obstaja temperaturno območje uparjanja. Domnevamo, da se temperatura zvišuje linearno v področju uparjanja. Zaradi osnosimetrične ponazoritve uparjalnika je treba podati ločene vrednosti temperature za vsak izmed cevnih lokov. Temperaturni robni pogoj se tako v področju uparjanja glasi:

where T_{sur} is the temperature of the surroundings (Table 1). In the case of an LPG binary mixture a temperature range of evaporation exists. We have supposed that the temperature in this region increases linearly. Due to the axisymmetrical approximation an individual value for the temperature has to be prescribed separately for each of the tube turns. The temperature boundary conditions in the region of the convective boiling of the binary mixture of propane and butane are written as:

$$T_{ref} = T_{bub} + \left(n_{cb} - 1\right)\Delta T_{cb} \tag{11}$$

kjer so: T_{bub} temperatura vrelišča binarne zmesi propana in butana, n_{cb} – število cevnih lokov, znotraj katerih poteka konvektivno uparjanje UNP-a, ΔT_{cb} pa je temperaturno območje med dvema sosednjima lokoma v področju uparjanja in je podano z izrazom:

where T_{bub} is the bubble-point temperature of the propane–butane mixture, n_{cb} is the number of tube turns in the region of convective boiling and ΔT_{cb} is the temperature difference between adjacent turns of the helically coiled tube in the region of convective boiling, defined by the expression

$$\Delta T_{cb} = \left(T_{dew} - T_{bub}\right)/n_{cb} \tag{12}$$

T_{dew} je temperatura rosišča binarne zmesi propana in butana. Tudi v področju pregrevanja parne faze UNP-a domnevamo linearno naraščanje temperaturnega poteka. Primerljiva temperatura je podana z izrazom:

T_{dew} is the dew-point temperature of the butane–propane mixture. In the superheating region the reference temperature is defined by the expression

$$T_{ref} = T_{dew} + \left(n_{\mathrm{sup}} - 1\right)\Delta T_{\mathrm{sup}} \tag{13}$$

kjer sta n_{sup} število cevnih lokov znotraj katerih poteka pregrevanje parne faze UNP-a, ΔT_{sup} pa temperaturna razlika med sosednjima lokoma v področju pregrevanja in je podana z enačbo:

where n_{sup} represents the number of tube turns in the region of the superheating of the propane–butane mixture, ΔT_{sup} is the temperature difference between adjacent tube turns in the superheating region defined by the expression:

$$\Delta T_{\mathrm{sup}} = \left(T_{out} - T_{dew}\right)/n_{\mathrm{sup}} \tag{14}$$

S T_{out} je označena temperatura pregrete parne faze UNP-a na izstopu iz uparjalnika.

where T_{out} is the outlet temperature of the propan–-butane vapour phase.

5.2 Enofazni tok v vijačni cevni spirali

Zaradi vijačne oblike pretočne poti so delci tekočine med pretokom izpostavljeni delovanju sredobežnih sil, kot posledica delovanja teh sil pa je prostorska struktura toka bistveno drugačna od tiste, ki jo poznamo pri ravnih ceveh. Tekočinski delci v bližini aksialne osi cevi se gibljejo z največjimi hitrostmi in so izpostavljeni večjim sredobežnim silam od počasneje se gibajočih delcev v neposredni bližini cevne stene. Posledica tega je struktura toka, v kateri se tekočina v središčnem področju cevi premika stran od krivinskega središča vijačnice, tekočina ob cevni steni pa prav nasprotno v smeri simetrijske osi vijačnice. Pojav je znan kot *sekundarno gibanje* v ukrivljenih vodih, ki se superponira na glavno vzdolžno smer toka. Tok se tako sestoji iz para spiralnih vijačnih vrtincev [26]. Odstopanja hidrodinamičnih in toplotnih karakteristik vijačnih cevi v primerjavi z ravnimi cevmi je mogoče pripisati prav pojavu sekundarnega gibanja. V splošnem je, v primerjavi z ravnimi cevmi ob enakih pogojih toka, prenos toplote izboljšan, tlačne izgube pa so nekoliko večje.

Za prehod iz laminarnega v turbulentni režim toka v vijačnih cevnih spiralah velja Schmidtova odvisnost [22], ki podaja kritično vrednost *Re* števila in se glasi:

5.2 Single-phase flow in helically coiled tubes

Because of the helical flow path the fluid particles are subjected to centrifugal forces. Because of this, the spatial flow structure is significantly different from the one which occurs in straight tubes. Fluid particles flowing close to the tube's longitudinal axis have the maximum velocity values and they are subjected to the maximum centrifugal forces in contrast to slowly moving particles in the vicinity of the tube walls. Liquid in the central part of the tube section moves away from the symmetry axis of helical tube. In contrast, liquid in the vicinity of the tube walls moves towards the helical tube symmetry axis. This phenomenon is known as *secondary flow* in curved pipes and it is superimposed on the main axial flow direction. Thus the flow consists of a pair of helical spiral vortices [26]. The hydrodynamic and heat-transfer characteristics are different in comparison with straight tubes and they can be attributed exclusively to the occurence of secondary flow. Normally, heat transfer and pressure losses in comparison with straight tubes under the same flow conditions are increased in helically coiled tubes.

For the laminar-to-turbulent flow transition in helically coiled tubes the Schmidt correlation [22] is used, which represents the critical value of the *Re* number as

$$\mathrm{Re}_{cr} = 2300\left[1+8,6\left(\frac{d_{in}}{D_{mc}}\right)^{0,45}\right] \qquad (15).$$

Reynoldsovo število je defirano kot $\mathrm{Re} = v \cdot d_{in} / \nu$, z d_{in} pa je označen notranji premer cevi vijačne cevne spirale. D_{mc} označuje prilagojeni premer vijačnice, ki upošteva vzpon vijačnice glede na vodoravno ravnino [25] in je podan z izrazom:

The Reynolds number is defined as $\mathrm{Re} = v \cdot d_{in} / \nu$, where d_{in} is the inner tube diameter of the helically coiled tube. D_{mc} represents the diameter of the modified coil, including the slope of the helical tube with respect to the horizontal plane [25], and is written as:

$$D_{mc} = D_c\left[1+\left(\frac{h_c}{\pi D_c}\right)^2\right] \qquad (16).$$

Z D_c je označen premer vijačnice, s h_c pa korak vzpona vijačnice. Schmidt [22] je ugotovil, da med laminarnim in popolnoma razvitim turbulentnim območjem obstaja prehodno območje toka, za katero velja $Re_{cr} < Re < 2.2x10^4$. Za določitev toplotne prestopnosti v področju turbulentnega toka podajamo odvisnost Gnielinskega [8], ki se glasi:

The helical coil diameter is D_c and h_c is the helical tube pitch. Schmidt [22] found that between the laminar and the turbulent flow region a transition region exists, where $Re_{cr} < Re < 2.2x10^4$. An estimation of the heat-transfer coefficient in the turbulent region can be made by means of the Gnielinski correlation [8], written as:

$$Nu = \frac{\xi/8 \cdot \mathrm{Re} \cdot \mathrm{Pr}}{1+12,7\sqrt{\xi/8}\,\left(\mathrm{Pr}^{2/3}-1\right)} \qquad (17),$$

kjer je ξ količnik trenja in je podan z izrazom:

where ξ is the friction factor defined as

$$\xi = \left[\frac{0.3164}{\mathrm{Re}^{0.25}} + 0,03\left(\frac{d_{in}}{D_{mc}}\right)^{0,5}\right] \qquad (18).$$

Pr je Prandtlovo število, ki je definirano s $\mathrm{Pr} = \mu \cdot c_p / \lambda$. Nusseltovo število je definirano z izrazom $Nu = \alpha \cdot d_{in} / \lambda$. Območje veljavnosti podanega izraza za določitev *Nu* števila ter tekočine, na katere se izraz nanaša, so podani v

Pr is the Prandtl number defined as $\mathrm{Pr} = \mu \cdot c_p / \lambda$ and the Nusselt number is defined as $Nu = \alpha \cdot d_{in} / \lambda$. The ranges within which the presented expression for the Nu number can be used and the fluids for which this correlation was derived are presented in [9] and [22].

[9] in [22]. Domnevamo, da ekstrapolacija tega izraza na območje parametrov postopkov, ki veljajo v našem primeru, ne povzroča večje napake izračuna.

We suppose that the extrapolation of the presented expression over the range of process parameters encountered in our computations will not significantly affect the results of the numerical analysis.

5.3 Konvektivno uparjanje v vijačni cevni spirali

5.3 Convective boiling in helically coiled tubes

Sistematično obdelanih podatkov o konvektivnem uparjanju zmesi propana in butana ni v dostopni literaturi. Enako velja za raziskave konvektivnega uparjanja binarnih zmesi v vijačnih cevnih spiralah ([3], [12] do [14] in [25]) . Zato smo omejeni na uporabo izrazov, ki veljajo za uparjanje najpogosteje raziskovanih binarnih zmesi (hladiva) v ravnih ceveh. Pri konvektivnem uparjanju binarnih zmesi je *konvektivno izparevanje* prevladujoč mehanizem spremembe agregatnega stanja. Področje *mehurčastega vrenja* je premaknjeno proti večjim vrednostim pregretja cevne stene ali pa se sploh ne pojavlja. Prispevek mehurčastega vrenja je pri konvektivnem uparjanju binarnih zmesi zadušen z učinki difuzije na medfaznih površinah rastočih mehurčkov.

Glede na intenzivnost zadušitve mehurčastega vrenja je Kandlikar [14] podal tri področja, za katera je predpisal različne izraze za določitev toplotne prestopnosti. Področja so definirana na podlagi vrednosti hlapljivosti V_1 in vrelnega števila Bo. Hlapljivost je definirana z izrazom:

Systematically assembled data on the convective flow boiling of prop–ne-butane mixtures cannot be found in the open literature. The same statement holds for convective flow boiling investigations of binary mixtures in helically coiled tubes ([3], [12] to [14] and [25]). Because of this we are restricted to using correlations derived for the boiling of frequently explored binary mixtures (refrigerants) in straight tubes. For binary mixtures boiling *convective evaporation* is the dominant mechanism of phase transformation. The *nucleate boiling* mechanism occurs at higher values of tube-wall superheating or it is not present at all. The contribution of nucleate boiling during the convective boiling of binary mixtures is suppressed by diffusion effects at the interfaces of growing bubbles.

With regard to the intensity of the suppression of the nucleation boiling process, Kandlikar [14] defined three regions where different expressions for the heat-transfer coefficient estimation can be used. The regions have been defined on the basis of volatility, V_1, and boiling number values, Bo. The volatility is written as

$$V_1 = \left(\frac{c_{p,l}}{h_{lv}}\right)\left(\frac{a}{D_{12}}\right)^{0.5}\frac{\mathrm{d}T}{\mathrm{d}x_1}\left(x_1 - y_1\right) \qquad (19),$$

kjer so: $c_{p,l}$ specifična toplota kapljevite faze, h_{lv} specifična uparjalna entalpija UNP-a, a toplotna difuzivnost, D_{12} snovska difuzivnost, x_1 molski delež komponente 1 v kapljeviti fazi in y_1 molski delež komponente 1 v parni fazi. Odvod $\mathrm{d}T/\mathrm{d}x_1$ določa strmino vrelne krivulje v diagramu T-x_1 ob določeni sestavi. Vrelno število Bo je definirano z izrazom:

where $c_{p,l}$ is the specific isobaric heat of the liquid phase, h_{lv} is the specific vaporisation enthalpy of LPG, a the heat diffusivity, D_{12} the molecular diffusivity, x_1 the mole fraction of component 1 in the liquid phase and y_1 the mole fraction of component 1 in the vapour phase. The derivative dT/dx_1 defines the slope of the bubble curve on the T-x_1 diagram for the selected mixture composition. The boiling number is defined as:

$$Bo = \frac{\dot{q}}{G \cdot h_{lv}} \qquad (20),$$

kjer je G gostota masnega toka. Snovske lastnosti zmesi propana in butana v primeru kapljevitega in plinastega agregatnega stanja so določene na podlagi izrazov iz [21] in [25].

Za izbrane parametre uparjanje poteka v področju zmerne zadušitve mehurčastega vrenja, povzročene z učinki difuzije (0,03 < V_1 < 0,2 in Bo > 1E-4). Področje prevladujočega mehurčastega vrenja ni več opazno. Konvektivno izparevanje je osnovni mehanizem prenosa toplote. Z difuzijo povzročena zadušitev je zmerna, vendar ne vpliva na člen mehurčastega vrenja v področju prevladujočega konvektivnega izparevanja. Dvofazna toplotna prestopnost v tem področju je podana z izrazom:

where G stands for the mass flux. The physical properties of the propane–butane mixtures in the liquid and gas states are calculated on the basis of expressions from references [21] and [25].

For selected process parameters the boiling occurs in the region of moderate suppression of nucleate boiling caused by diffusion (0.03 < V_1 < 0.2 in Bo > 1E-4). The region where nucleate boiling is the dominant mechanism does not exist. The governing heat-transfer mechanism is convective evaporation. Suppression caused by diffusion still exists, but its moderate contribution does not affect the nucleate boiling term in the region where convective evaporation dominates. The two-phase heat-transfer coefficient in this region is written as

$$\alpha_{TP,CBD} = \alpha_{lo}\left(1-x\right)^{0.8}\left[1,136\cdot Co^{-0.9}\cdot f_2\left(Fr_{lo}\right)+667,2\cdot Bo^{0.7}\cdot F_{fl,m}\right] \tag{21}$$

V enačbi (21) so: α_{lo} enofazna toplotna prestopnost, za primer, da celoten tok zaseda kapljevita faza, x masni delež parne faze, Co konvektivno število, $f_2(Fr_{lo})$ množitelj Froudovega števila in $F_{fl,m}$ parameter, ki je odvisen od lastnosti tekočine in površine cevne stene. Konvektivno število je definirano z izrazom:

In expression (21), α_{lo} is the single-phase all-liquid heat-transfer coefficient, x is the mass fraction of the vapour phase or the quality, Co is the convection number, Fr_{lo} is the Froude number with all flow as liquid and $f_2(Fr_{lo})$ is the Froude number multiplier. $F_{fl,m}$ is a fluid–surface parameter that depends on the fluid and the heater surface characteristics. The convective number is defined as:

$$Co = \left(\frac{\rho_v}{\rho_l}\right)^{0,5}\left[\frac{(1-x)}{x}\right]^{0,8} \tag{22}$$

kjer sta ρ_v gostota parne faze in ρ_l gostota kapljevite faze. Množitelj Froudovega števila ima vrednost 1 za pokončne in vodoravne cevi z vrednostjo $Fr_{lo} > 0,4$. Za $Fr_{lo} \leq 0,4$ pri vodoravnih ceveh je vrednost $f_2(Fr_{lo})$ definirana z izrazom $(25Fr_{lo})^{0,3}$. Froudovo število za primer, da celoten tok zaseda kapljevita faza, je definirano z izrazom:

where ρ_v and ρ_l are the density of the vapour and the liquid phases, respectively. The Froude number multiplier is 1 for vertical tubes and for horizontal tubes with $Fr_{lo} > 0.4$. For $Fr_{lo} \leq 0.4$ at horizontal tubes the value of $f_2(Fr_{lo})$ is $(25Fr_{lo})^{0.3}$. The Fr number with all flow as the liquid is defined as

$$Fr_{lo} = \frac{G^2}{\rho_l^2\cdot g\cdot d_{in}} \tag{23}$$

Parameter učinkov stične površine [14] je določen z vzvodnim pravilom in se glasi:

Fluid–surface parameters [14] are defined by the mixing rule as

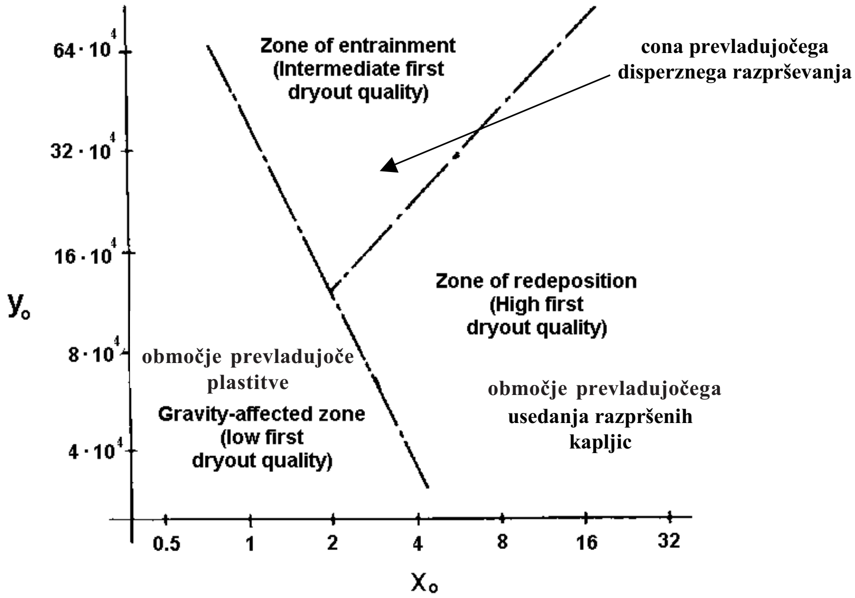
$$F_{fl,m} = x_1 F_{fl,1} + x_2 F_{fl,2} \tag{24}$$

Podani izrazi veljajo za področje popolne omočenosti cevne stene. V področju izsuševanja cevne stene se razmere spremenijo zaradi postopnega razširjanja neomočenega dela cevnega oboda. Parametri, ki najbolj vplivajo na razmere v področju izsuševanja, so sistemski tlak p, premer vijačnice D_c, gostota toplotnega toka $\dot{q}$ in gostota masnega toka G. Berthoud in Jayanti [4] sta na podlagi vpliva sistemskih parametrov določila tri karakteristična področja, v katerih prevladuje eden izmed vodilnih mehanizmov izsuševanja, in sicer: (a) področje prevladujočega disperznega razprševanja, (b) področje prevladujočega usedanja razpršenih kapljic in (c) področje prevladujoče plastitve toka. Na sliki 4 je prikazan diagram, s katerim določimo cono prevladujočih mehanizmov izsuševanja cevne stene v vijačni cevni spirali.

Brezrazsežno število $x_0 = G\big/\left(\rho_v\sqrt{gD_c}\right)$ podaja vpliv sredobežnih sil, ki delujejo na parno fazo toka in v njej razpršene kapljice. Vpliv tega števila je najbolj pomemben v področju prevladujočega vnovičnega usedanja razpršenih kapljic. Brezrazsežno število $y_0 = G\cdot d_{in}\cdot\left(d_{in}/0,02\right)^{1/2}\big/\mu_l$ je Re število kapljevite faze toka, ki je spremenimo s popravnim količnikom notranjega cevnega premera. Vpliv tega števila je prevladujoč v področju razprševanja kapljic v parno jedro toka. Za podane sistemske parametre uparjalnika je plastovito izsuševanje cevne stene prevladujoč mehanizem. Izraz za določitev masnega deleža parne faze ob začetni izsušitvi za področje

The expressions given above can be used if the tube walls are completely wetted. In the region of tube-wall dryout, the conditions are changed as non-wetted portions of the tube walls are gradually spread. The main system parameters leading to the tube-wall dryout process are the system pressure p, the helical coil diameter D_c and the heat and mass flux, $\dot{q}$ and G, respectively. By analysing the system parameters Berthoud and Jayanti [4] defined three regions with different governing mechanisms of dryout: (a) region where the dispersed entrainment is dominant, (b) region with the intensified redeposition of dispersed drops and (c) region where the flow-stratification effects dominate. In Figure 4 different zones of governing dryout mechanisms in helically coiled tubes are presented.

The nondimensional number $x_0 = G\big/\left(\rho_v\sqrt{gD_c}\right)$ accounts for the centrifugal forces's influence on vapour phase and the dispersed drops in it. The value of this number is large in the region with the intensified redeposition of dispersed drops. The nondimensional number $y_0 = G\cdot d_{in}\cdot\left(d_{in}/0,02\right)^{1/2}\big/\mu_l$ is the Re number for liquid-phase flow with a modified value of the inside tube diameter. The value of this number is large in the region of the dispersed entrainment in the vapour core of the flow. For selected system parameters the stratification or gravity-dominated dryout of the tube walls is the governing mechanism. The mass quality at the initial stage of dryout for the region in which



Sl.4 *Območja prevladujočih mehanizmov izsuševanja v vijačni cevni spirali [4]*
Fig. 4. *Zones of different dryout mechanisms in helically coiled tubes [4]*

prevladujočega vpliva plastovitosti toka oz. težnostnih sil se glasi [4]:

stratification dryout is the governing mechanism can be calculated by the expression [4]:

$$x_{ini} = 10^{7,068}\left(\frac{\rho_l}{\rho v}\right)^{-2,378}\left(\frac{Gd_{in}}{\mu_l}\right)^{-1,712}\left(\frac{G}{\rho_v\sqrt{gD_c}}\right)^{0,967}\left(\frac{\dot{q}}{Gh_{lv}}\right)^{-0,740} \tag{25}$$

kjer je μ_l dinamična viskoznost kapljevite faze. Za praktične namene velja ugotovitev, da se popolna izsušitev cevne stene pojavi za ravnotežni masni delež parne faze z vrednostjo x_{tot} = 1. Pri plastnem izsuševanju se točka začetne izsušitve pojavi v zgornji točki cevnega oboda, nato pa se izsušitev simetrično razširja po cevnem obodu. Končni izraz za določitev toplotne prestopnosti v vijačni cevni spirali [25] se glasi:

where μ_l is the dynamic viscosity of the liquid phase. For practical purposes the total dryout of the tube walls can be considered to occur at mass quality x_{tot} = 1. When stratification is the governing mechanism of dryout, the initial dryout point appears at the uppermost circumferential tube position. Thereafter, dryout is symmetrically spread along the tube walls. Thus, the final expression for the estimation of heat-transfer coefficient within the helically coiled tube is written as:

$$\alpha = \alpha_{TP}(1-\Theta) + \alpha_{EP}\Theta \tag{26}$$

kjer so: Θ trenutni kot omočenja cevne stene v področju uparjanja, α_{EP} toplotna prestopnost v enofaznem področju in α_{TP} toplotna prestopnost v dvofaznem področju (konvektivno uparjanje).

where Θ is the temporary angular position of the dryout propagation front in the convective boiling region, α_{EP} is the heat-transfer coefficient in the single-phase region of flow and α_{TP} is the heat-transfer coefficient in the region of two-phase flow.

5.4 Obtekanje plašča uparjalnika

Uparjalnik je v večini primerov nameščen na odprtem prostoru. Za določitev toplotnih izgub v okolico je treba podati toplotno prestopnost pri obtekanju plašča uparjalnika. Zaradi spremenljivih tokovnih razmer okrog posode uparjalnika je določitev toplotne prestopnosti zelo težavna. Za obtekanje valjaste posode uparjalnika smo uporabili znano odvisnost Churchilla in Bernsteina, ki velja za široko področje *Re* in *Pr* števil. Odvisnost velja ob pogoju $Re \cdot Pr > 0,2$ in se glasi:

5.4 Flow around the revaporizer vessel

Revaporizers are mainly manufactured without any thermal insulation. The heat-transfer coefficient for air flow around the revaporizer has to be defined if we want to allow for heat loses to the surroundings. Unsteadiness of the flow conditions around the revaporizer's shell can make such an estimation very difficult. For the flow around the cylindrical shell the well-known correlation of Churchill and Bernstein is used. The correlation is applicable to a wide range of Re and Pr numbers with the only restriction being $Re \cdot Pr > 0.2$:

$$Nu = 0,3 + \frac{0,62\,\mathrm{Re}^{1/2}\,\mathrm{Pr}^{1/3}}{\left[1+\left(0,4/\mathrm{Pr}\right)^{2/3}\right]^{1/4}}\left[1+\left(\frac{\mathrm{Re}}{282000}\right)^{5/8}\right]^{4/5} \qquad (27).$$

Snovske lastnosti veljajo za suh zrak. Hitrost zračnih tokov je upoštevana s povprečno vrednostjo hitrosti vetra, ki je usmerjena normalno na plašč uparjalnika. Pri obtekanju dna in pokrova posode smo uporabili izraz:

In equation (27) the physical properties for the dry air are selected. The velocity of the air flow is included by means of an average value of the wind velocity normal to the revaporizer shell. For flow along the bottom and the cover of the revaporizer a correlation for the turbulent flow region is used:

$$Nu = 0,037 \cdot \mathrm{Re}^{0.8}\,\mathrm{Pr}^{1/3} \qquad (28),$$

ki velja za turbulentno področje in je podan v [1].

and it has been taken from [1].

5.5 Električno uporovno gretje [2]

Prostornino, ki jo zaseda električni grelnik, smo nadomestili z porozno snovjo. Gostota toplotnega toka, ki je predpisana na robovih porozne snovi, je izračunana iz moči grelnika in njegove površine. Enačba, ki povezuje električne in toplotne veličine grelnika, se glasi:

5.5 Electrical resistance heating [2]

The revaporizer section where the electrical heater is placed was modelled as a porous region. The heat flux prescribed at boundaries of the porous heater can be calculated from heater's electric power and its surface area, as given by the expression

$$P_{el} = I^2 R_{el} = I^2\left(\frac{\rho_{el} L_w}{S_w}\right) = \frac{V_{el}^{\,2}}{R_{el}} = \dot{Q}_{ht} = \dot{q}_{ht} \cdot A_{ht} \qquad (29).$$

Pri določitvi poroznosti in prepustnosti poroznega grelnika smo upoštevali navodila, ki so podana v [7]. V izrazu (29) so: P_{el} električna moč grelnika, $\dot{Q}_{ht}$ toplotna moč grelnika, $\dot{q}_{ht}$ gostota toplotnega toka grelnika in A_{ht} njegova površina.

where P_{el} is the electrical power, $\dot{Q}_{ht}$ is the power of the heater, $\dot{q}_{ht}$ is the heat flux and A_{ht} its surface area. The instruction given in [7] was taken into consideration when the porosity and the permeability of the porous heater were defined.

6 RAČUNSKI ALGORITEM

Računski algoritem, s katerim smo prišli do rešitve, je podan na sliki 5.

6 CALCULATION ALGORITHM

The calculation algorithm used to obtain the final solution of the defined problem is presented in Fig. 5.

7 REZULTATI

Računalniški program FIDAP 8.5 omogoča nastanek nestrukturirane mreže končnih elementov. Uporabljen je algoritem oblaganja za diskretizacijo računskega območja, pri čemer je opravljeno lokalno zgoščevanje mreže ob robovih računskega območja (stene posode in cevni loki). Po testiranju občutljivosti numeričnih rezultatov na gostoto mreže je bila kot primerna izbrana računska mreža s 14.900 elementi v področju toka sekundarne kapljevine in 1900 elementi v področju poroznega grelnika. Hitrosti v polju naravne konvekcije so majhne, tokovni režim je laminaren.

Postopek izračuna (slika 5) smo ponovili tolikokrat, da smo dosegli ujemanje toplotnega toka, ki ga cevni snop sprejme v področju uparjanja $\dot{Q}_{cb}$ in uparjalne entalpije UNP-a $\dot{Q}_{lv}$. Na koncu je doseženo stanje, v katerem so se rezultati nadaljnje določitve povprečne gostote toplotnega toka v področju uparjanja spreminjali le znotraj območja enega cevnega loka. To je obenem tudi največja mogoča natančnost tukaj vpeljanega postopka. Rezultati, ki so bili doseženi v zadnjem koraku izračuna, so podani v nadaljevanju.

7 RESULTS

Unstructured finite-element grids can be created with the FIDAP 8.5 program package. For the computational-region mesh generation we used the paving algorithm. Local mesh refinement in the vicinity of all the region boundaries was carried out. The study of the influence of the grid density on the numerical results resulted in an optimum mesh density with 14,900 finite elements in the region of the secondary liquid flow and 1900 elements in the region of the porous heater. The flow regime was laminar since the *Re* number value for the natural convection inside the secondary liquid flow was below the critical value.

The calculation procedure (Figure 5) had to be repeated several times before we achieved the final operational stage where the total heat received by the tube bundle in the convective boiling region $\dot{Q}_{cb}$ was equal to the vaporisation enthalpy of the LPG $\dot{Q}_{lv}$. The results obtained in the last iteration of the calculation procedure served as the basis for the discussion of the results. Convective boiling occurs inside the 21 turns of the tube bundle. The mass

Preglednica 2. *Toplotni tokovi vzdolž robov računskega območja ob pogoju nespremenljive vrednosti gostote toplotnega toka (prvi računski korak)*
Table 2. *Heat fluxes through the computational domain boundaries (first calculation step – uniform heat-flux distribution along tube bundle assumed when the boundary conditions are defined)*

Rob Boundary	Toplotni tok [W] Heat flow rate [W]	Rob Boundary	Toplotni tok [W] Heat flow rate [W]
lok1 turn1	30,20	**lok17 turn17**	352,20
lok2 turn2	42,30	**lok18 turn18**	341,80
lok3 turn3	51,10	**lok19 turn19**	338,20
lok4 turn4	62,20	**lok20 turn20**	334,30
lok5 turn5	70,00	**lok21 turn21**	332,10
lok6 turn6	79,40	**lok22 turn22**	281,30
lok7 turn7	89,20	**lok23 turn23**	242,00
lok8 turn8	92,30	**lok24 turn24**	212,80
lok9 turn9	101,80	**lok25 turn25**	171,70
lok10 turn10	111,30	**lok26 turn26**	114,10
lok11 turn11	118,10	**lok27 turn27**	82,30
lok12 turn12	122,20	**lok28 turn28**	43,10
lok13 turn13	131,40	**pokrov cover**	34,10
lok14 turn14	138,60	**plašč shell**	185,10
lok15 turn15	328,50	**dno bottom**	25,10
lok16 turn16	341,20	Σ	5000

Konvektivno uparjanje poteka znotraj 21 cevnih lokov. Masni delež parne faze ob začetni izsušitvi znaša $x_{ini} = 0,41$. Število cevnih lokov, znotraj katerega je opazna popolna omočenost cevnega oboda, je 9. Znotraj 12 lokov poteka izsuševanje cevne stene. Od tod naprej poteka pregrevanje parne faze UNP-a. Za podane parametre je to stanje ustaljenega delovanja uparjalnika.

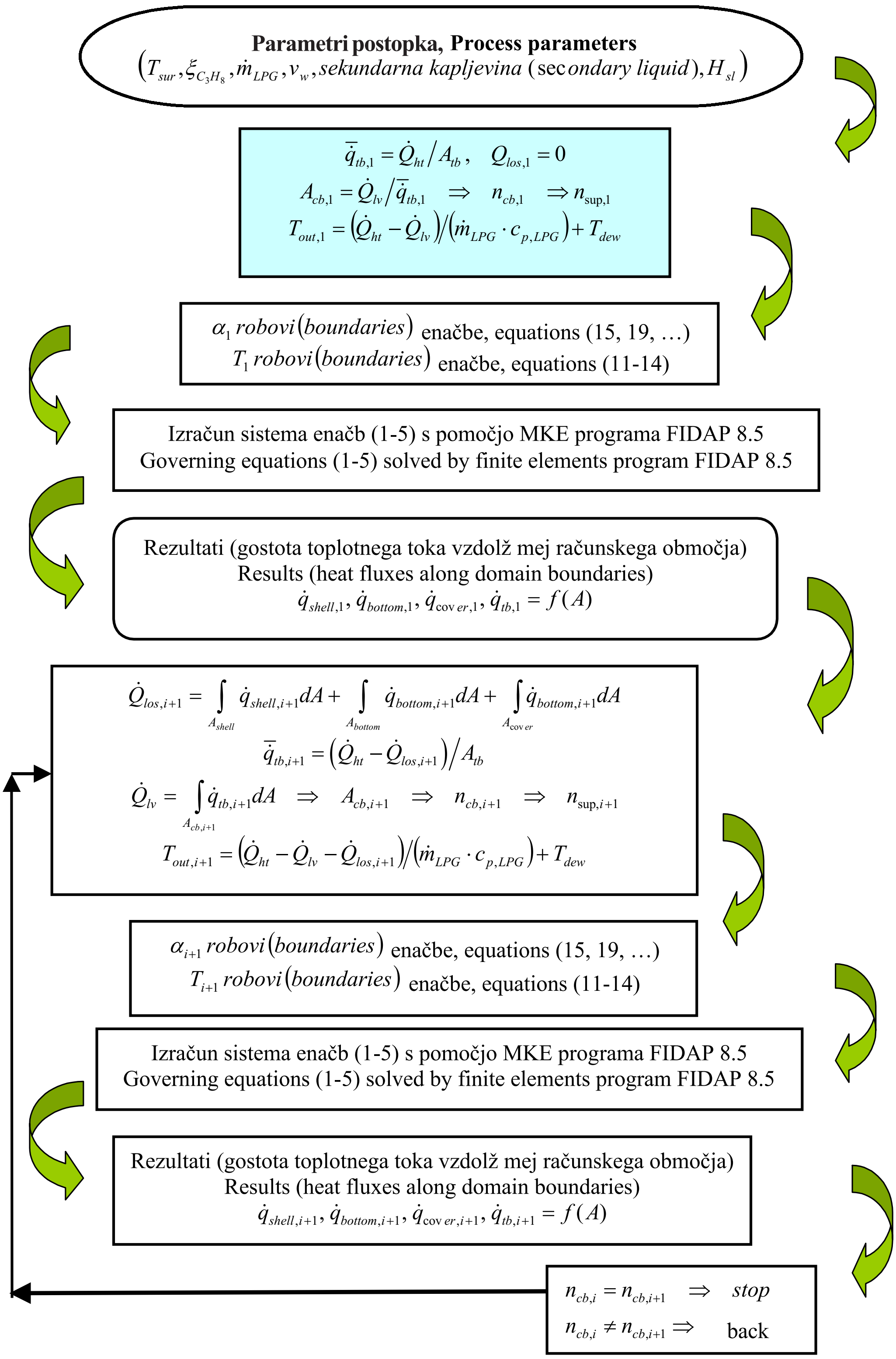
V preglednici 2 so podane vrednosti toplotnih tokov, ki jih sprejmejo posamezni loki cevnega snopa ob pogoju stalne vrednosti gostote toplotnega toka, ki prehaja na cevni snop (začetna domneva). V preglednici 3 so podane vrednosti toplotnih tokov po posameznih lokih cevnega snopa v zadnjem računskem koraku, in sicer, ko je upoštevana neenakomerna porazdelitev gostote toplotnega toka po posameznih lokih cevnega snopa (končno stanje).

Na sliki 6 je podan potek toplotne prestopnosti in temperature (robni pogoji) po posameznih cevnih lokih cevnega snopa v prvem koraku izračuna

quality of the vapour phase at the initial dryout position has a value $x_{ini} = 0.41$. It was found that the total wetting of the tube walls is present inside the first 9 turns of the tube bundle. Dryout of the tube walls takes place inside the next 12 turns of the tube bundle. From that point to the outlet of the tube bundle the superheating of the LPG occurs. For the prescribed working parameters of the revaporizer this is the steady-state operating regime.

In Table 2 the heat-flow values received by particular turns of the tube bundle are presented. As an initial assumption the uniform heat flux distribution along the tube bundle was assumed when correlations to estimate boundary conditions were used. In Table 3 the heat-flow values received by the particular turns of the tube bundle in the last calculating step are presented.

There is nonuniformity of the heat-flow distribution along the tube bundle, and it was taken into account when defining the boundary conditions



Sl.5 *Računski algoritem*
Fig. 5. *Calculating algorithm*

(nespremenljiva gostota toplotnega toka vzdolž cevnega snopa). Na sliki 7 je prikazan potek toplotne prestopnosti in temperature v zadnjem računskem koraku.

Na sliki 8a) je prikazan izsek hitrostnega polja v osnosimetričnem prerezu uparjalnika, od koder je

in the next calculating steps. The heat-transfer coefficient and the temperature distribution along tube turns are presented in Figures 6 and 7, in the first and last calculating step, respectively.

In Figure 8(a) the velocity field in the vicinity of the upper part of the electrical heater is presented. It is evident

Preglednica 3. *Toplotni tokovi vzdolž robov računskega območja v zadnjem računskem koraku, ko je upoštevana neenakomernost gostote toplotnega toka (končno stanje)*
Table 3. *Heat fluxes through the computational domain boundaries (final calculation step – nonuniform heat-flux distribution along the tube bundle taken into account when the boundary conditions are defined)*

Rob Boundary	Toplotni tok [*W*] Heat flow rate [*W*]	Rob Boundary	Toplotni tok [*W*] Heat flow rate [*W*]
lok1 **turn1**	60,00	**lok17** **turn17**	356,00
lok2 **turn2**	65,50	**lok18** **turn18**	366,00
lok3 **turn3**	68,50	**lok19** **turn19**	366,50
lok4 **turn4**	73,00	**lok20** **turn20**	367,00
lok5 **turn5**	82,50	**lok21** **turn21**	368,50
lok6 **turn6**	89,00	**lok22** **turn22**	260,00
lok7 **turn7**	95,50	**lok23** **turn23**	215,50
lok8 **turn8**	102,50	**lok24** **turn24**	106,00
lok9 **turn9**	106,00	**lok25** **turn25**	96,00
lok10 **turn10**	114,50	**lok26** **turn26**	50,50
lok11 **turn11**	119,50	**lok27** **turn27**	49,50
lok12 **turn12**	125,50	**lok28** **turn28**	48,50
lok13 **turn13**	132,00	**pokrov** **cover**	32,00
lok14 **turn14**	139,50	**plašč** **shell**	261,50
lok15 **turn15**	321,50	**dno** **bottom**	25,50
lok16 **turn16**	336,00	Σ	5000

razvidno, da so največje hitrosti grelne kapljevine največje v središčnih območjih uparjalnika (notranjost grelnika). Najmanjše hitrosti sekundarne kapljevine se pojavijo v bližini plašča uparjalnika.

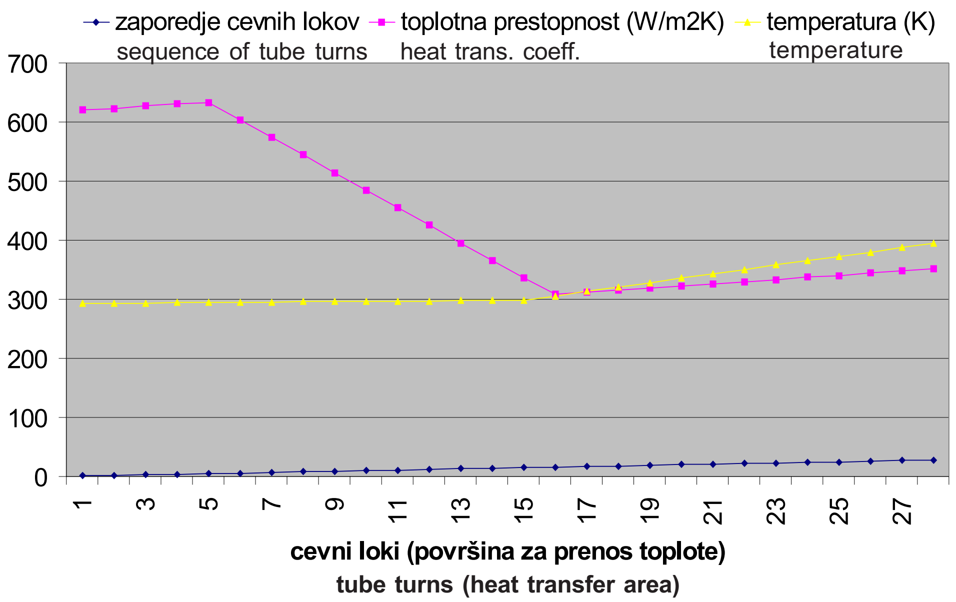
Na sliki 8b) je podan izsek temperaturnega polja v osnosimetričnem prerezu uparjalnika. Področje konvektivnega uparjanja zaseda največji del cevnega snopa. Področje majhne temperaturne razlike med sekundarno kapljevino in cevno steno je vzrok, da je konvektivno izparevanje vodilni mehanizem agregatne spremembe (temnejša področja na sliki 8b). V zgornjem delu električnega grelnika so temperature sekundarne kapljevine največje (slika 8b), vendar pa ne presegajo največje dopustne vrednosti, ki je predpisana s strani proizvajalca (130 °C).

Izstopna temperatura pregrete parne faze UNP-a je podatek, ki smo ga uporabili za preverjanje doseženih rezultatov. Polje naravne konvekcije v uparjalniku je uporabljeno za prenos krmilne veličine od izstopnega loka cevnega snopa na zaznavala

that the maximum velocities of the secondary liquid arise in the central part of the revaporizer (internal section of electrical heater). In contarast, the minimum velocities occur immediately in the vicinity of the revaporizer shell.

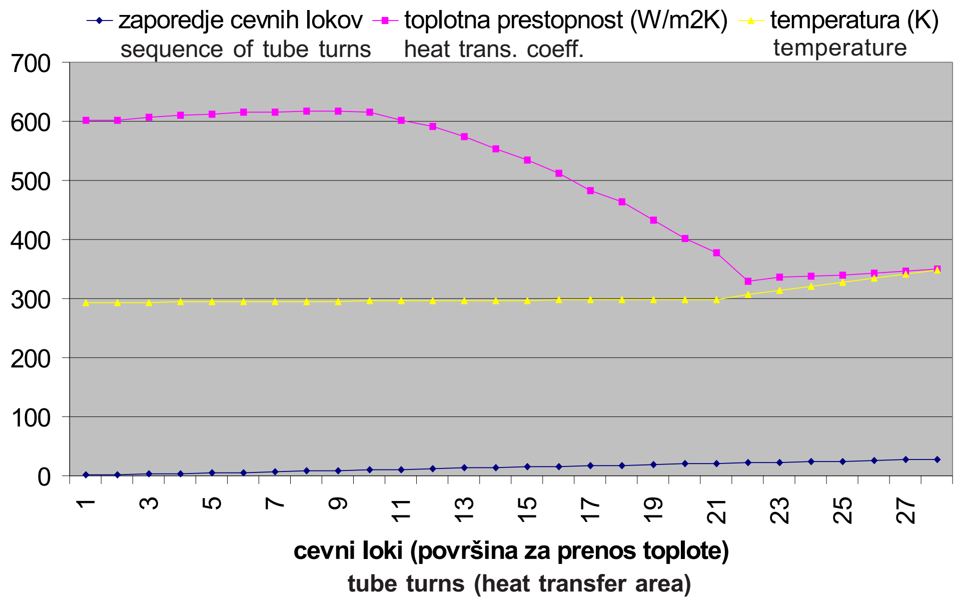
In Figure 8(b) the temperature field in the same view as in Figure 8(a) is shown. It is evident that convective boiling occupies the largest part of the tube bundle. The low temperature difference between the secondary liquid and the tube wall is the reason why the convective evaporation – as a mode of the boiling process – is the governing mechanism of the phase transition (dark regions of the plot). In the upper sections of the electrical heater the temperature reaches its maximum (see Figure 9), but its value does not exceed the allowed value prescribed by the manufacturer (130 °C).

The outlet temperature of the LPG superheated vapour phase is the parameter used for the verification of the achieved results of the numerical analysis. The natural convection field was used for regulating the value transport between the



Sl.6. *Potek toplotne prestopnosti in temperature po posameznih lokih cevnega snopa v prvem računskem koraku (robni pogoji - začetni računski korak)*

Fig. 6. *Heat-transfer coefficient and temperature distribution along the turns of the tube bundle in the first calculation step (boundary conditions – initial state)*

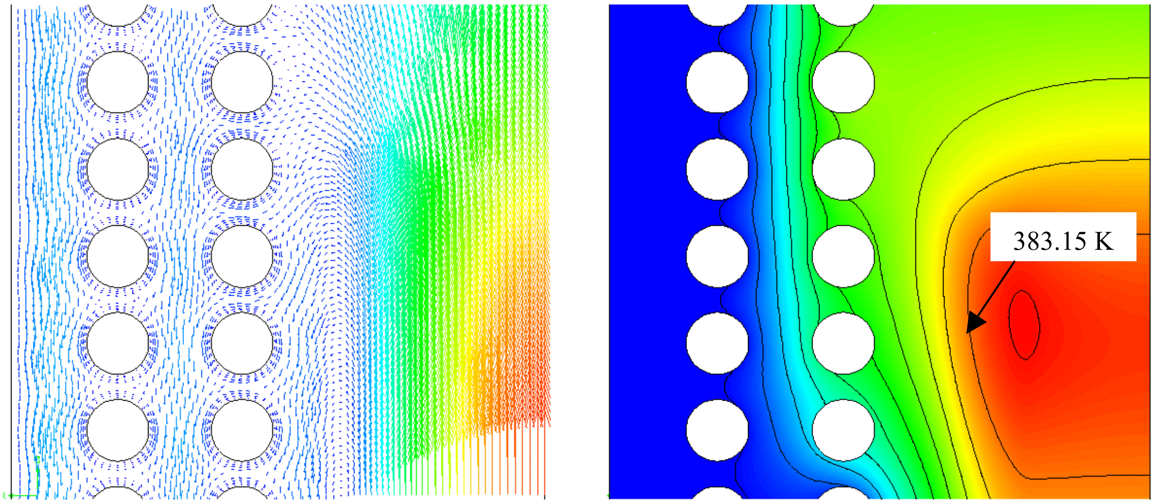


Sl.7. *Potek toplotne prestopnosti in temperature po posameznih lokih cevnega snopa, ko je doseženo končno obratovalno stanje (robni pogoji - zadnji računski korak)*

Fig. 7. *Heat-transfer coefficient and temperature distribution along the turns of the tube bundle in the last calculation step (boundary conditions – final state)*

krmilnih termostatov. Krmiljena veličina je temperatura. Za obratovanje uparjalnika je potrebno, da je temperaturno polje v točki namestitve zaznaval krmilnih termostatov vedno v predpisanem delovnem območju. Delovno območje krmilnih termostatov je od 65 °C do 85 °C. Na podlagi poteka izoterm temperaturnega polja smo ugotovili, da je temperatura v točkah namestitve krmilnih termostatov znotraj predpisanega temperaturnega območja. Temperatura v točki namestitve zaznavala termostata, ki krmili

last turn of tube bundle and the sensor of the control thermostats. The controlled value is the temperature. Undisturbed operating of the revaporizer requires that the temperature value at the thermostat sensor position has to be always within the defined temperature range. The working range of the control thermostats is from 65 °C to 85 °C. Using an isotherms plot it was found that the temperature at the location of the control thermostats lies within the defined temperature range. The temperature at the position of the thermostat



Sl.8. *Potek (a) hitrostnega in (b) temperaturnega polja v osnosimetričnem prerezu uparjalnika v področju zgornjega dela grelnika*

Fig. 8. *(a) Velocity and (b) temperature field in axisymmetrical section of revaporizer in the region of upper parts of heater*

delovanje elektromagnetnega ventila, znaša 76 °C. Doseženo stanje velja ob izbranih parametrih postopka (preglednica 1). Krmilni termostati so oprema uparjalnika, ki daje določene podatke o celostnih značilnostih delovanja naprave. Za vpogled v krajevne razmere v posameznih delih uparjalnika so potrebne podrobne meritve izbranih fizikalnih veličin. Na sliki 9 je podan prikaz temperaturnega polja v točkah namestitve tipal krmilnih termostatov.

8 SKLEPI

Sočasen nastop večjega števila prenosnih pojavov onemogoča natančno obravnavo obnašanja uparjalnika. Zapletena geometrijska oblika cevnega snopa in električnega grelnika omejuje možnosti uporabe znanih metod dimenzioniranja in nadzora dvofaznih prenosnikov toplote. Uporaba standardnih računskih postopkov za dimenzioniranje uparjalnikov je v danem primeru nezadostna. V splošnem je zelo malo empiričnih podatkov o toplotni prestopnosti pri tokovih z naravno konvekcijo v zapletenih geometrijskih oblikah. Vodilni prenosni pojav v električnem uparjalniku je konvektivno uparjanje ukapljenega naftnega plina. Pravilno vrednotenje tega pojava je zahtevna inženirska naloga.

Pri izračunu smo domnevali, da se uparjalnik obnaša približno kot sistem z vsiljeno nespremenljivo gostoto toplotnega toka. Čeprav je krajevna porazdelitev gostote toplotnega toka neenakomerna, je povprečna vrednost le-te nespremenljiva in določena z močjo in površino grelnika (sistem s posrednim električnim gretjem). Rezultati so pokazali, da se uparjalnik obnaša kot sistem z vsiljeno temperaturno razliko (zunanje področje cevnega snopa), delno pa kot sistem z vsiljeno gostoto toplotnega toka (notranje področje

sensor controlling the electromagnetic valve has a value of 76 °C. This operating state corresponds to the selected process parameters (Table 1). In Figure 9 the temperature field in the uppermost part of the revaporizer axisymmetrical section is presented. To get a better insight into the local conditions in particular parts of the revaporizer more accurate measurements should be performed, and their results compared with the computational results.

8 CONCLUSIONS

Due to different transport phenomena occuring in the revaporizer it is impossible to achieve an exact solution of the heat and flow conditions inside the device. The complex tube bundle and the electrical heater geometry restricts the implementation of well-known methods for design and rating calculations of two-phase heat exchangers. In the open literature there are not, in general, empirical data about heat-transfer coefficients due to natural convection in the systems with complex geometry. Likewise, convective boiling of LPG in helically coiled tubes is an unexplored phenomenon. The correct treatment of the latter is a demanding engineering task.

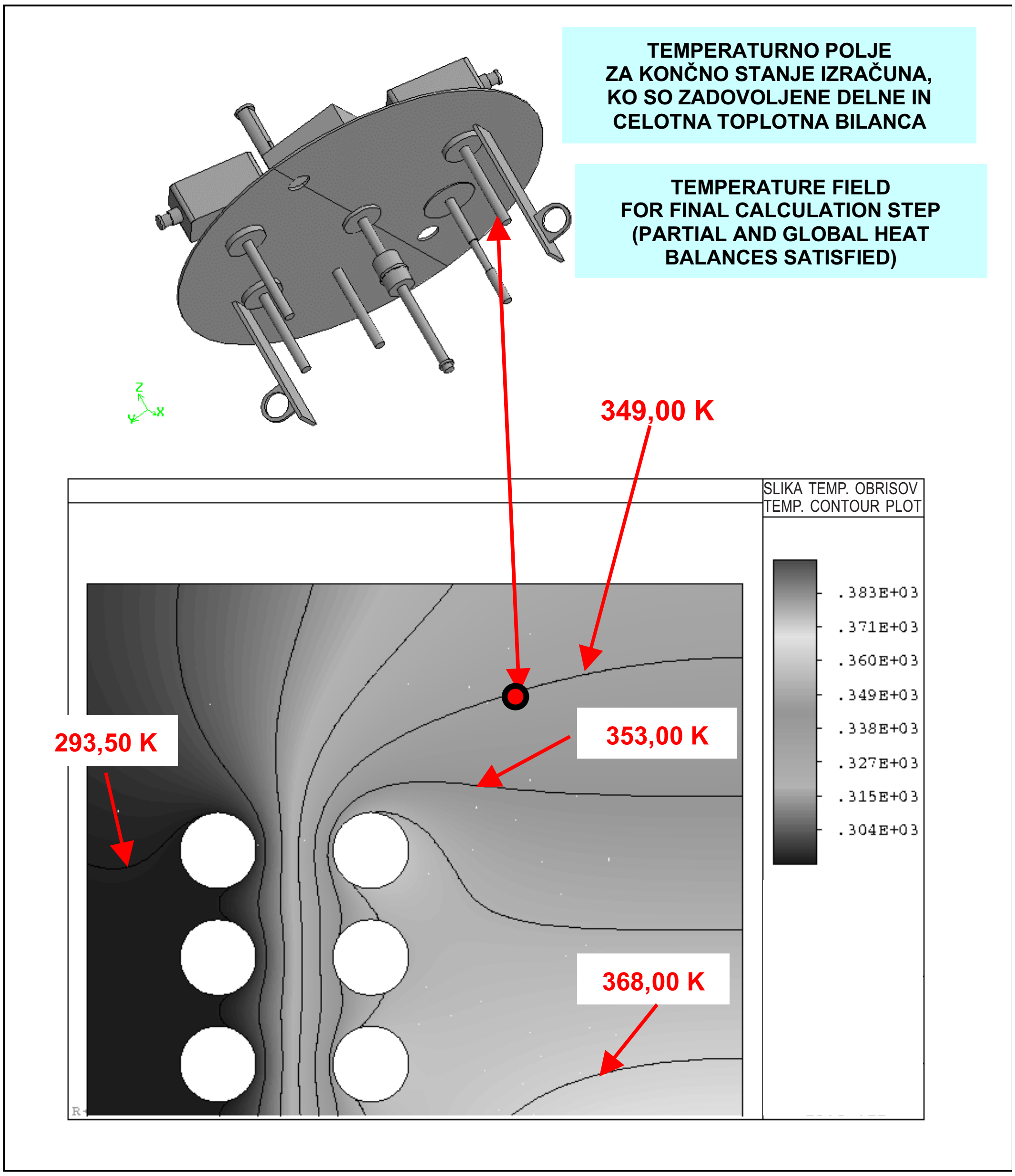
In our approach we assumed that the revaporizer operates as a system with a constantly imposed heat flux. Although the local distribution of heat flux exhibits considerable nonuniformity its averaged value is constant, defined by the heat power and the surface area of the electric heater (system with indirect electrical heating). It can be concluded that the revaporizer operates partly as a system with an imposed temperature difference (external region of the tube bundle) and partly as a system with an imposed heat flux (internal region of the tube bundle).

cevnega snopa). Uporabo preverjene Kandlikarjeve zveze za ravne cevi pri vrednotenju nasičenega uparjanja znotraj vijačne cevne spirale je mogoče pojasniti z nizko vrednostjo gostote toplotnega in masnega toka ter zanemarljivim vplivom centrifugalnih sil. Ker razpršitev ni prevladujoč pojav v področju obročastega toka, je omenjeno povezanost mogoče kombinirati z zvezo za čisto parno fazo in tako določiti toplotno prestopnost v področju izsuševanja cevne stene.

Krajevne razmere so za predpisovanje robnih pogojev na mejah računskega območja odločilnega pomena. Robni pogoji na mejah področja, kjer poteka uparjanje, so zato predpisani na temelju dandanes

The implementation of Kandlikar's correlation for the heat-transfer characteristics' estimation for saturated boiling in helically coiled tubes can be explained by the low heat and mass flux values and the negligible effects caused by centrifugal forces. Due to the fact that the dispersed entrainment is not a dominant phenomenon in the region where annular flow regime exists, Kandlikar's correlation can be combined with the correlation for the heat-transfer coefficient's estimation in the region of the all-vapour phase flow. Thus it is possible to define the heat-transfer coefficient in the dryout region of the tube bundle.

Local conditions in the revaporizer are of great importance when boundary conditions have to be



Sl. 9. *Potek temperaturnega polja v zgornjem delu uparjalnika (temperatura v točki namestitve tipala krmilnega termostata elektromagnetnega ventila)*

Fig. 9. *Temperature field in the upper part of the revaporizer (temperature is shown at the position where the thermostat sensor of the electromagnetic valve is placed)*

najbolj uveljavljenih odvisnosti. Celostni kazalniki obnašanja uparjalnika so po opravljenem toplotnem uravnoteženju pokazali veljavnost vpeljanih hipotez. Za izbrane delovne parametre je temperatura v točki namestitve zaznaval krmilnih termostatov uparjalnika dosegla predpisane vrednosti. Uparjalnik deluje znotraj predpisanega temperaturnega območja v merilnih točkah. Zadovoljene so bile delne in celotna toplotna bilanca. Kolikšen je pomen morebitnih napak, ki izvirajo iz ekstrapolacije uporabljenih odvisnosti na uparjanje UNP-a v vijačni cevni spirali, ni znano. Analiza obratovanja uparjalnika v ekstremnih razmerah oz. na mejah delovnega področja bo pokazala velikost teh napak.

prescribed. Boundary conditions on the boundaries where convective boiling takes place are prescribed on the basis of verified correlations. The observed integral characteristics of the revaporizer confirmed the correctness of our assumptions. For the selected combination of process parameters the temperature at the control sensor is within the prescribed temperature range. The local and global heat balances are satisfied. Some deviations can arise from the extrapolation of used correlations outside of the prescribed ranges. An analysis of the revaporizer operating in extreme conditions, that is in the vicinity of the borders of the working diagram can show the magnitude of these deviations.

9 OZNAKE
9 NOMENCLATURE

toplotna difuzivnost	a	thermal diffusivity
površina	A	area
vrelno število	Bo	Boiling number
konvektivno število	Co	Convective number
specifična izobarna toplota	c_p	specific heat at constant pressure
premer	D	diameter
premer cevi	d	tube diameter
difuzivnost	D_{12}	diffusion coefficient
množitelj Fr števila	$f_2(Fr_{lo})$	Fr number multiplicator
Froudovo število	Fr	Froude number
gostota masnega toka	G	mass flux
težnostni pospešek	g	acceleration due to gravity
specifična entalpija, korak vzpona vijačnice	h	specific enthalpy, helix pitch
višina	H	height
jakost električnega toka	I	electric flow rate
masni pretok	$\dot{m}$	mass flow rate
število cevnih lokov	n	number of tube turns
Nusseltovo število	Nu	Nusselt number
termodinamični tlak	p	thermodynamic pressure
Prandtlovo število	Pr	Prandtl number
gostota toplotnega toka	$\dot{q}$	heat flux
toplotni tok	$\dot{Q}$	heat flow rate
upor prevoda toplote, električna upornost	R	thermal resistance, electric resistance
Reynoldsovo število	Re	Reynolds number
prečni prerez električnega voda	S	transversal section of electrical conductor
čas	t	time
temperatura	T	temperature
hitrost	u, v	velocity
absolutna vrednost hitrostnega vektorja	$\|u\|$	absolute value of velocity vector
hlapljivost, električna napetost	V	volatility
masni delež parne faze, molski delež komponente v kapljeviti fazi	x	quality, mole fraction in liquid phase
molski delež komponente v parni fazi	y	mole fraction in vapour phase
Grški simboli		**Greek Symbols**
efektivna dinamična viskoznost	$\bar{\mu}$	effective dynamic viscosity
koeficient vztrajnosti porozne snovi	ϖ	porous inertia coefficient
modificirana toplotna prestopnost	α^*	modified heat-transfer coefficient
poroznost	ϕ	porosity
debelina cevne stene	δ	tube-wall thickness
dinamična viskoznost	μ	dynamics viscosity

gostota, specifična električna upornost	ρ	density, specific electric resistance
kinematična viskoznost	ν	kinematics viscosity
koeficient upora, masni delež	ξ	friction factor, mass fraction
kot omočenja cevne stene v področju uparjanja	Θ	tube-wall wetting angle in the boiling region
toplotna prestopnost	α	heat-transfer coefficient
toplotna prevodnost	λ	heat conductivity
permeabilnost porozne snovi	κ_I	porous permeability
prostorninski temperaturni raztezek	β_T	volumetric temperature dilatation coefficient
temperaturna razlika med sosednjima cevnima lokoma	ΔT	temperature difference between adjacent tube turns

Podpisi		**Subscripts**
vrelišče	*bub*	bubble point
vijačnica	*c*	helix
propan	C_3H_8	propan
konvektivno vrenje	*cb*	convective boiling
področje prevladujočega konvektivnega izparevanja	*CBD*	convective evaporation dominant region
rosišče	*dew*	dew point
električna veličina	*el*	electrical value
enofazno področje	*EP*	single-phase region
stična površina	*fl*	contact surface
grelnik	*ht*	heater
notranja vijačnica	*ic*	inside helix
notranji	*in*	interior
začetna vrednost	*ini*	initial value
kapljevita faza	*l*	liquid phase
celoten tok zaseda kapljevita faza	*lo*	all-flow liquid
toplotne izgube	*los*	heat losses
kapljevina - para	*lv*	liquid–vapour
modificirana vijačnica	*mc*	modified helix
zunanja vijačnica	*oc*	outside helix
optimalna vrednost veličine	*opt*	optimum value
zunanji	*out*	outer
referenčna vrednost	*ref, 0*	reference value
plašč	*s*	shell
sekundarna kapljevina	*sl*	secondary liquid
pregrevanje	*sup*	superheating
okolica	*sur*	surroundings
cevni snop	*tb*	tube bundle
končna vrednost	*tot*	final value
dvofazno področje	*TP*	two-phase region
ukapljeni naftni plin	*LPG*	liquified petroleum gas
parna faza	*v*	vapour phase
zračni tokovi okrog plašča, prevodna žica	*w*	air flow around vaporizer, conducting wire

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