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Model stenskega uparjanja za popis podhlajenega vrenja toka pri nizkih tlakih

Wall-Evaporation Model for a Description of Sub-Cooled Flow Boiling under Low-Pressure Conditions

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V prispevku je predstavljen model stenskega uparjanja za popis podhlajenega vrenja pri nizkih tlakih. Model temelji na lokalnih mehanizmih nukleacije mehurčkov in obsega vpliv debelitve toplotne mejne plasti ob greti steni. Model smo vključili v enorazsežni termo-hidravlični program RELAP5. Spremenjeni program smo testirali na številnih nizkotlačnih preizkusih podhlajenega vrenja iz literature ([1] do [4]). V nasprotju s sedanjim programom smo dosegli zelo dobro ujemanje izračunov z meritvami.

(Ključne besede: uparjanje stensko, vrenje toka podhlajeno, programi termohidravlični, RELAP5)

In this paper we propose a wall-evaporation model for sub-cooled flow boiling under low pressures. The model is based on local mechanisms of bubble nucleation and captures the effect of the developing thermal boundary layer near the heated wall. The model was incorporated into the one-dimensional thermal-hydraulic code RELAP5. The modified code was validated against a number of published low-pressure sub-cooled boiling experiments ([1] to [4]), and in contrast to the existing code it shows good agreement with the experimental data.

(Keywords: hot wall evaporation, sub-cooled flow boiling, thermal-hydraulic code, RELAP5)

0 UVOD

Podhlajeno vrenje toka se pojavi, ko ob greti steni kanala nastaja para, kljub temu da je povprečna temperatura toka kapljevine po prerezu toka nižja od temperature vrelišča. Pojav je posebej pomemben v jedrskih reaktorjih hlajenih z vodo, pri katerih parni mehurčki v sredici vplivajo na obnašanje reaktorskega sistema, tako med normalnim obratovanjem kot tudi v primeru nezgodnih scenarijev.

Za celovite analize prehodnih pojavov v hladilnih sistemih jedrskih reaktorjev se večinoma uporabljajo enorazsežni termohidravlični programi (RELAP5, TRAC, CATHARE, ATHLET). V zadnjih letih se je zaradi potreb po varnostnih analizah raziskovalnih jedrskih reaktorjev, ki obratujejo pri nizkih tlakih, in zaradi raziskav koncepta hlajenja zbiralnika zadrževalnega hrama prihodnjih

0 INTRODUCTION

Sub-cooled flow boiling occurs when vapour is produced as a cold liquid flows along a heated channel, even though the average liquid temperature over the channel cross-section is lower than the liquid saturation temperature. The phenomenon is especially important in water-cooled nuclear power reactors, where the presence of vapour bubbles in the core influences the behaviour of the reactor system, either during normal operation or in the case of accident scenarios.

To perform integral simulations of the transient phenomena in nuclear-reactor coolant systems one-dimensional thermal-hydraulic codes (such as RELAP5, TRAC, CATHARE and ATHLET) are widely used. In recent years, the interest in numerically simulating sub-cooled flow boiling at low pressures (1 to 3 bar) has increased, driven by the need to perform lahkovodnih reaktorjev (PLVR - ALWR) povečalo zanimanje za numerične simulacije podhlajenega vrenja toka pri nizkih tlakih (1 do 3 bar). Vendar je večina konstitucijskih modelov v današnjih termohidravličnih programih razvita in preverjena pri visokih tlakih (zaradi uporabnosti v jedrskih elektrarnah), zato jih ne moremo brez sprememb uporabiti za preračune nizkotlačnih sistemov. Eden od glavnih ciljev razvijalcev programov je razširitev uporabnosti celovitih programov tudi v območje nizkih tlakov.

V zadnjem času je bilo z različnimi termohidravličnimi programi izvedenih več simulacij podhlajenega vrenja pri nizkih tlakih. Rezultati analiz modelov podhlajenega vrenja ([5] do [8]), ki se uporabljajo v sedanjih termohidravličnih programih, so pokazali, da je izračunani delež parne faze pri nizkih tlakih mnogo nižji kakor tisti v preizkusih. Pri nizkih tlakih je razlika med gostotama kapljevine in pare bistveno večja kakor pri visokih tlakih (1:1590 pri 1 bar, 1:6.2 pri 150 bar), zato enaka količina nastale pare zavzame bistveno večjo prostornino. Pri visokih tlakih so parni mehurčki razmeroma majhni, medtem ko so pri nizkih tlakih le-ti bistveno večji. Večanje deleža parne faze vzdolž toka je tako močno odvisno od spremembe velikosti mehurčkov. V splošnem na količino proizvedene pare med pojavom podhlajenega vrenja vplivajo različni fizikalni mehanizmi, kakor so stensko uparjanje, kondenzacija parnih mehurčkov v podhlajeni kapljevini, koncentracija medfazne površine (določena z velikostjo mehurčkov) in medfazno trenje. V tem prispevku smo posebej obravnavali modeliranje stenskega uparjanja. Predlagali smo novi posplošeni model stenskega uparjanja za uporabo v termohidravličnih programih in ga vključili v program RELAP5.

1 MODEL STENSKEGA UPARJANJA

Model stenskega uparjanja popisuje hitrost generacije parnih mehurčkov na greti površini stene. Predstavljen je enorazsežni model stenskega uparjanja za uporabo v termohidravličnih programih. Pri razvoju modela smo upoštevali naslednje predpostavke:

1. V razmerah nasičenja, v katerih sta kapljevina in para v toplotnem ravnovesju ($T_l=T_g=T_{sat}$), se celotni dovedeni toplotni tok porabi samo za generacijo pare.
2. Model uparjanja mora temeljiti na osnovnih

safety analyses of research nuclear reactors operating at low pressures and to investigate the sump-cooling concept for advanced light-water reactors (ALWR). However, as most of the constitutive models in present-day thermal-hydraulic codes have been developed and validated for high-pressure conditions (due to the relevance for nuclear power plants), they cannot be straightforwardly applied for calculations involving low-pressure systems. One of the main goals of code developers is to extend the applicability of current integral codes to the low-pressure region.

Recently, several simulations of sub-cooled boiling under low-pressure conditions using different thermal-hydraulic codes have been performed. The results of analyses of the sub-cooled boiling models ([5] to [8]) used in the current thermal-hydraulic codes have shown that, at low pressures, the calculated void fraction is significantly lower than in experiments. At low pressures, the difference between the liquid and vapour densities is much higher than at high pressures (1:1590 at 1 bar, 1:6.2 at 150 bar); therefore, the same amount of generated vapour occupies a significantly larger volume. The vapour bubbles are relatively small at high pressures, whereas they are much larger at low pressures. The increasing of the void fraction along the flow therefore strongly depends on the change of bubble size. In general, the amount of vapour produced during the sub-cooled flow boiling process is governed by different physical mechanisms, such as wall evaporation, the condensation of vapour bubbles in a sub-cooled liquid, the interfacial area concentration (determined by the bubble size) and the interfacial drag between the phases. In this paper we focus on the modelling of wall evaporation. A new generic wall-evaporation model for application in thermal-hydraulic codes is proposed and incorporated into the RELAP5 code.

1 THE WALL-EVAPORATION MODEL

The wall-evaporation model describes the generation rate of vapour bubbles on a heated wall surface. A one-dimensional wall evaporation model for implementation in thermal-hydraulic codes is presented. When developing the model, the following assumptions were taken into account:

1. Under saturation conditions, where the liquid and vapour are in thermal equilibrium ($T_l=T_g=T_{sat}$), the entire wall heat flux has to be used for vapour generation.
2. The model of wall evaporation has to be based on the basic parameters that describe bubble nucleation:

parametrih, ki opisujejo mehurčkasto vrenje: velikost mehurčka, gostota nukleacijskih jeder N_a in frekvenca nukleacije mehurčkov f.

3. Pri nizkih tlakih mora biti delež toplotnega toka za uparjanje bistveno večji kakor v modelih stenskega uparjanja, ki se uporabljajo v sedanjih termohidravličnih programih. Kakor je navedeno v literaturi, termohidravlična programa RELAP5 ([7] in [8]) in ATHLET [5] napovesta prenizko hitrost stenskega uparjanja.

Hitrost stenskega uparjanja lahko določimo z uporabo t.i. modela razdelitve toplotnega toka, ki predpostavlja, da se celotni dovedeni toplotni tok porabi delno za uparjanje pregrete kapljevine v mejni plasti tik ob greti površini in delno za segrevanje podhlajene kapljevine v jedru toka. Za osnovo pri razvoju modela stenskega uparjanja smo uporabili model razdelitve dovedenega toplotnega toka Kurula in Podowskega [9]. Po njunem modelu je vsaka enota grete površine razdeljena na dva dela: prvi del obsega vplivno območje nukleacije mehurčkov A_{bub}, medtem ko na preostalem delu grete površine $A_{1\phi}$ poteka konvektivni prenos toplote s stene na kapljevino. A_{bub} in $A_{1\phi}$ v brezrazsežni obliki pomenita deleže celotne grete površine:

bubble size, the number of active nucleation sites per unit surface and the nucleation frequency of the bubbles.

3. Under low-pressure conditions, the fraction of wall heat flux used for wall evaporation must be significantly higher than in the wall-evaporation models used in the existing thermal-hydraulic codes. According to the literature, the thermal-hydraulic codes RELAP5 ([7] and [8]) and ATHLET [5] predict a wall-evaporation rate that is too low.

The wall-evaporation rate can be determined from the so-called heat-flux partitioning model, which assumes that the total applied heat flux is consumed partially for the evaporation of the superheated liquid in the boundary layer adjacent to the heated surface and partially for the heating of the sub-cooled liquid in the core flow. As a basis for the development of the wall-evaporation model, the heat-flux partitioning model of Kurul and Podowski [9] was used. According to their model, each unit of the heated surface consists of two parts: the first part of the heated area occupies the influence area of bubble nucleation, A_{bub}, whereas single-phase convection from the wall to the liquid takes place on the remaining part of the heated area, $A_{1\phi}$. In non-dimensional form, A_{bub} and $A_{1\phi}$ represent the fractions of the total heated area:

$$A_{bub} + A_{1\phi} = 1 \qquad (1).$$

Celotni dovedeni toplotni tok iz stene na dvofazni vrelni tok sestoji iz treh različnih komponent (sl. 1):

The total heat flux transferred from the wall to the two-phase boiling flow consists of three different components (Figure 1):

$$q_w = q_{1\phi} + q_Q + q_e \qquad (2),$$

kjer:

- $q_{1\phi}$ označuje toplotni tok zaradi enofazne konvekcije, ki se vrši zunaj vplivnega območja nukleacije mehurčkov;
- q_Q označuje toplotni tok zaradi površinskega hlajenja znotraj vplivnega območja mehurčkov A_{bub} (to je prenos toplote s stene na podhlajeno kapljevino, ki periodično zapolnjuje izpraznjen prostor mehurčkov, ki se trgajo s stene med nukleacijskim krogom);
- q_e označuje uparjalni toplotni tok, ki se porablja za neposredno generacijo parnih mehurčkov.

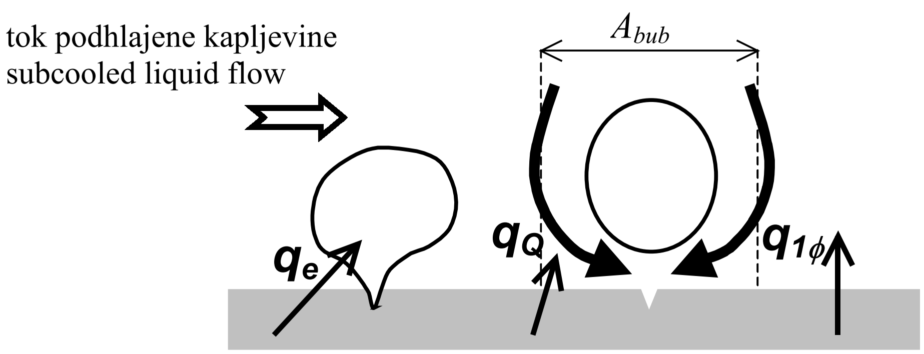
Vplivna površina mehurčkov na enoto površine stene A_{bub} je definirana kot:

where:

- $q_{1\phi}$ denotes the single-phase convection heat flux that takes place outside the influence area of the bubble nucleation,
- q_Q denotes the surface-quenching heat flux within the bubble influence area, A_{bub} (i.e., the heat transferred from the wall to the sub-cooled bulk liquid that periodically fills the volume vacated by the departing bubbles during the bubble nucleation cycle),
- q_e denotes the wall-evaporation heat flux that is used for the direct generation of vapour bubbles.

The bubble influence area per unit wall area, A_{bub}, is determined as:

$$A_{bub} = \min\left[1, N_a K\left(\frac{\pi d_{bw}^2}{4}\right)\right] \qquad (3),$$



Sl. 1. *Porazdelitev toplotnega toka na steni*
Fig. 1. *Heat-flux partitioning at the wall*

kjer sta N_a gostota aktivnih nukleacijskih jeder in d_{bw} premer mehurčkov, nastalih na greti steni. Premer d_{bw} je izračunan z uporabo Unalove korelacije [10], ki upošteva vpliv tlaka, podhladitve kapljevine, dovedenega toplotnega toka in hitrosti toka na velikost mehurčka. Parameter K določa velikost vplivnega območja mehurčka v okolici nukleacijskega jedra. Navadno se vzame nespremenljiva vrednost parametra $K = 4$ [11]. Pri največji gostoti aktivnih nukleacijskih jeder N_a vplivno območje mehurčkov pokriva celotno greto površino (A_{bub}= 1). Pri vrednosti K= 4 vplivna površina mehurčkov postane enaka celotni greti površini, kadar povprečni razmik med dvema sosednjima nukleacijskima jedroma doseže velikost dveh premerov mehurčka (2 d_{bw}).

Osnovni model Kurula in Podowskega [9] smo prilagodili za uporabo v enorazsežnih termohidravličnih programih, ki uporabljajo spremenljivke povprečene po prečnem prerezu kanala. Uparjalni toplotni tok je sorazmeren gostoti aktivnih nukleacijskih jeder N_a, frekvenci nukleacije mehurčkov f, masi mehurčka in uparjalni toploti h_{lg}:

where N_a is the density of active nucleation sites and d_{bw} is the diameter of the bubbles generated on the heated wall. The diameter d_{bw} is calculated from the Unal correlation [10], which takes into account the effects of pressure, liquid sub-cooling, heat flux and liquid flow velocity on the bubble size. The parameter K determines the size of the bubble influence area around the nucleation site. A constant value of $K = 4$ is assumed [11]. At the maximum density of nucleation sites, N_a, the bubble influence area covers the entire heating surface (A_{bub}= 1). At the value of K= 4, the bubble influence area becomes equal to the total heating surface if the average spacing between two neighbouring nucleation sites reaches the size of two bubble diameters (2 d_{bw}).

The basic model of Kurul and Podowski [9] has been adapted for application in one-dimensional thermal-hydraulic codes, which use variables averaged over the channel cross-section. The evaporation heat flux is proportional to the density of nucleation sites, N_a, the mass of a single bubble, the bubble nucleation frequency, f , and the latent heat, h_{lg}:

$$q_e = N_a f\left(\frac{\pi}{6} d_{bw}^3\right)\rho_g h_{\lg} \tag{4}$$

Frekvenca nukleacije mehurčkov je definirana po Coleu (1960, citirano v Ivey [12]):

The bubble nucleation frequency is defined by Cole (1960, cited by Ivey [12]):

$$f = \sqrt{\frac{4}{3}\frac{g(\rho_l - \rho_g)}{d_{bw}\rho_l}} \tag{5}$$

kjer je f odvisen samo od premera mehurčka d_{bw} in od gostot faz ρ_l in ρ_g. Toplotni tok zaradi površinskega hlajenja izračunamo kot:

where f is affected only by the bubble diameter, d_{bw}, and by the phase densities ρ_l and ρ_g. The quenching heat flux is calculated as:

$$q_Q = h_Q A_{bub}\left(T_w - T_l\right)\cdot\xi \tag{6}$$

kjer so h_Q toplotna prestopnost, T_w temperatura stene in T_l povprečna temperatura kapljevine. Koeficient h_Q izračunamo tako, da upoštevamo časovno odvisen prevod toplote s stene na polneskončno kapljevino [11]:

where h_Q is the heat-transfer coefficient, T_w is the wall temperature, and T_l is the average liquid temperature. The coefficient h_Q is calculated by considering transient conduction from the wall to a semi-infinite liquid [11]:

$$h_Q = \frac{1,6f}{\sqrt{\pi}}\sqrt{k_l \rho_l c_{pl}} \qquad (7).$$

Komponenta toplotnega toka enofazne konvekcije zunaj vplivnega območja mehurčkov je izračunana takole:

The single-phase convection heat-flux component outside the bubble influence area is calculated in the following way:

$$q_{1\phi} = h_{1\phi}\cdot(1-A_{bub})\cdot(T_w - T_l)\cdot\xi \qquad (8),$$

kjer je toplotna prestopnost $h_{1\phi}$ za enofazni turbulentni konvektivni tok, izračunana po Kurulu in Podowskem [9]:

where the heat-transfer coefficient $h_{1\phi}$ for the single-phase turbulent convective flow is calculated according to Kurul and Podowski [9]:

$$h_{1\phi} = St\cdot\rho_l\cdot c_{pl}\cdot u_l \qquad (9),$$

kjer je St Stantonovo število. Faktor ξ smo vključili v en. (6) in (8) za segrevanje kapljevine, da bi zadostili pogoju, da se pri nasičenju celotni dovedeni toplotni tok porabi za generacijo pare:

where St is the Stanton number. The inhibiting factor ξ was introduced in Eqs. (6) and (8) for the liquid-heating components to satisfy the condition that at saturation, the entire wall heat flux is consumed for vapour generation:

$$\xi = \frac{2\cdot\left(h_{lsat}-h_l\right)/\left(h_{lsat}-h_{lcr}\right)}{1+\left(h_{lsat}-h_l\right)/\left(h_{lsat}-h_{lcr}\right)} \qquad (10).$$

Faktor ξ je padajoča funkcija podhladitve kapljevine in popisuje dvorazsežno naravo razvijajoče se toplotne mejne plasti ob steni, kjer so temperaturni gradienti največji. Z debelitvijo plasti vzdolž kanala se vedno več kapljevine uparja, medtem ko je vedno manj toplote na voljo za segrevanje kapljevine. Kritična entalpija h_{lcr}, ki je izračunana po korelaciji Saha-Zuber [13], označuje mesto, kjer postane vpliv toplotne mejne plasti pomemben.

Temperaturo stene T_w in temperaturo kapljevine T_l v en. (6) in (8) izračunamo z implicitno sklopitvijo energijske enačbe in enačbe za prevod toplote v steni [14], tako da je gostota nukleacijskih jeder N_a edina preostala neznana veličina. Iz vsote komponent dovedenega toplotnega toka lahko izračunamo neznano vrednost N_a:

The factor ξ is a decreasing function of the liquid sub-cooling and captures the two-dimensional nature of the developing thermal boundary layer near the heated wall, where the liquid temperature gradient is significant. As the layer gets thicker along the channel, more vapour is being generated, thus less heat is transferred to the liquid. The critical enthalpy, h_{lcr}, calculated from the Saha-Zuber correlation [13], defines the location where the effect of the thermal boundary layer becomes significant.

The wall temperature, T_w, and average liquid temperature, T_l, in Eqs. (6) and (8) are calculated by the implicit coupling of the energy equation and the equation for the heat-transfer conduction through the wall [14], so that N_a remains the only unknown variable. The unknown value of N_a can be calculated from the sum of the heat-flux components:

$$N_a = \frac{q_w - h_{1\phi}(T_w - T_l)\cdot\xi}{\pi\cdot d_{bw}^2\left[f\,\frac{1}{6}d_{bw}\cdot h_{fg}\cdot\rho_g(1+\varepsilon)-\left(\frac{K}{4}\right)h_{1\phi}(T_w-T_l)\cdot\xi\right]} \qquad (11),$$

kjer je ε faktor površinskega hlajenja, ki je definiran kot razmerje med toplotnima tokovoma q_Q in q_e:

where ε is the quenching factor, defined as the ratio between heat fluxes q_Q and q_e:

$$\varepsilon = \frac{q_Q}{q_e} = \left(\frac{3}{2}K\right)\frac{h_Q\cdot\tau_q(T_w-T_l)}{d_{bw}\cdot\rho_g\cdot h_{\mathrm{lg}}}\cdot\xi \qquad (12).$$

Ko poznamo vrednosti komponent dovedenega toplotnega toka, lahko iz uparjalnega toplotnega toka q_e izračunamo hitrost stenskega uparjanja. Hitrost stenskega uparjanja Γ_w je definirana kot količina pare na enoto časa in prostornine, ki nastaja v pregreti toplotni mejni plasti kapljevine ob steni:

Knowing the values of the heat-flux components, the wall-evaporation rate can be calculated from the evaporation heat flux, q_e. The wall-evaporation rate, Γ_w, is defined as the amount of steam per unit time and unit volume generated in the superheated liquid thermal boundary layer near the wall:

$$\Gamma_w = \frac{q_e \cdot A_w}{V \cdot h_{\mathrm{lg}}} \qquad (13),$$

kjer sta A_w in V greta površina in prostornina računske celice.

where A_w and V are the heated area and the volume of the computational cell.

2 VKLJUČITEV MODELA V PROGRAM RELAP5

2 INCLUSION OF THE MODEL IN THE RELAP5 CODE

Termohidravlični program RELAP5 se zelo pogosto uporablja za izvajanje varnostnih analiz v jedrskih reaktorjih. Sedanji program RELAP5 uporablja Laheyev model [15] za izračun stenskega uparjanja. Naše predhodne analize [7] so pokazale, da Laheyev model izračuna prenizke hitrosti uparjanja pri preizkusnih podhlajenega vrenja, izvedenih pri tlakih pod 3 bar. Model ne upošteva eksplicitno premera mehurčka, ki pri nizkih tlakih bistveno vpliva na hitrost stenskega uparjanja in posledično na količino pare v vrelnem kanalu. Zato smo v zadnjo razpoložljivo verzijo programa RELAP5/MOD3.2.2 Gamma vključili novi model stenskega uparjanja. Program temelji na dvofluidnem sistemu neravnotežnih enorazsežnih transportnih enačb [14] za prenos:
mase:

The thermal-hydraulic code RELAP5 is frequently used to perform safety analyses of nuclear reactors. The existing code RELAP5 uses Lahey's model [15] to calculate wall evaporation. Our previous analyses [7] have shown that Lahey's model calculates evaporation rates that are too low, for sub-cooled boiling experiments performed at pressures below 3 bar. The model does not explicitly take into account the bubble size, which significantly affects the wall-evaporation rate at low pressures, and consequently the amount of vapour in the boiling channel. Thus, the new wall-evaporation model was included in the latest available code version RELAP5/MOD3.2.2. Gamma. The code is based on the two-fluid system of non-equilibrium one-dimensional transport equations [14] for
mass

$$\frac{\partial}{\partial t}\left(\alpha_k \rho_k\right) + \frac{1}{A}\frac{\partial}{\partial x}\left(\alpha_k \rho_k v_k A\right) = \Gamma_k \qquad (14),$$

gibalne količine:

momentum

$$\alpha_k\ \rho_k \frac{\partial}{\partial t} v_k + \frac{1}{2}\alpha_k \rho_k \frac{\partial}{\partial x} v_k^2 = -\alpha_k \frac{\partial}{\partial x} p + \alpha_k \rho_k g\ + WFR_k + \Gamma_k\left(v_{ik} - v_k\right)\ - C_i \left|v_r\right| v_r - C_{VM} a_{VM} \qquad (15),$$

in notranje energije:

and internal energy

$$\frac{\partial}{\partial t}\left(\alpha_k \rho_k e_k\right) + \frac{1}{A}\frac{\partial}{\partial x}\left(\alpha_k \rho_k e_k v_k A\right) = -p\frac{\partial}{\partial t}\alpha_k - \frac{p}{A}\frac{\partial}{\partial x}\left(\alpha_k v_k A\right) + Q_{wk} + Q_{ik} + \Gamma_k h_k + DISS_k \qquad (16),$$

kjer se spodnji indeks k nanaša bodisi na kapljevito fazo ($k=l$) bodisi na plinasto fazo ($k=g$). Členi na levi strani enačb (14) do (16) opisujejo spremembo fizikalnih veličin po času in kraju. Člen izmenjave mase na desni strani en. (14) lahko razdelimo na prenos mase na medfaznem stiku pare in kapljevine Γ_{ik} (kondenzacija) in na prenos mase zaradi

where the subscript k refers either to the liquid phase ($k=l$) or to the gas phase ($k=g$). The terms on the left-hand side of Eqs. (14–16) describe the variation of physical variables in time and space. The mass-exchange term on the right-hand side of Eq. (14) can be divided into the mass-transfer term at the vapour-liquid interface, Γ_{ik} (e.g., condensation) and the mass-uparjanja v toplotni mejni plasti ob steni Γ_w (stensko uparjanje):

transfer due to evaporation in the wall's thermal boundary layer, Γ_w (wall evaporation):

$$\Gamma_k = \Gamma_{ik} + \Gamma_w \qquad (17).$$

Členi na desni strani gibalne en. (15) po vrsti pomenijo: silo tlaka, silo teže, trenje ob steni, prenos gibalne količine zaradi izmenjave mase med fazama, medfazno trenje in silo navidezne mase. Prva dva člena na desni strani energijske en. (16) pomenita delo tlaka, tretji člen toplotni tok, ki prehaja s stene na fazo *k*, četrti člen medfazni prenos toplote, peti člen prenos notranje energije zaradi izmenjave mase med fazama in zadnji člen disipacijo notranje energije zaradi stenskega trenja.

Prenos mase, energije in gibalne količine med fazama in med dvofaznim tokom in steno je popisan z dodatnimi zapiralnimi enačbami [14]. V primeru podhlajenega vrenja v toku, se medfazna kondenzacija ($\Gamma_{ik} < 0$) in stensko uparjanje ($\Gamma_w \geq 0$) pojavljata sočasno. Hitrost stenskega uparjanja Γ_w je definirana z en. (13).

The terms on the right-hand side of the momentum Eq. (15) represent, respectively, the pressure gradient, the body force, the wall friction, the momentum transfer due to mass exchange, the interfacial drag force and the virtual mass force. The first two terms on the right-hand side of Eq. (16) represent the pressure work, the third term represents the heat flux from the wall to phase *k*, the fourth term describes the interfacial heat transfer, the fifth term describes the internal energy transport due to mass exchange and the last term represents the energy dissipation due to wall friction.

The transfer of mass, energy and momentum between the phases and between the two-phase flow and the wall is described by additional closure equations [14]. In the case of sub-cooled boiling flow, interfacial condensation ($\Gamma_{ik} < 0$) and wall evaporation ($\Gamma_w \geq 0$) occur simultaneously. The wall-evaporation rate, Γ_w, is defined by Eq. (13).

3 REZULTATI IN RAZPRAVA

Pri podhlajenem vrenju toka je neto količina pare v kanalu odvisna od interakcije med stenskim uparjanjem, kondenzacijo in relativno hitrostjo mehurčkov glede na kapljevino. Ker je glavni namen prispevka modeliranje stenskega uparjanja, podrobnosti modeliranja preostalih mehanizmov niso obravnavane (najdemo jih lahko v [16]). Nabor zapiralnih enačb za stensko uparjanje, kondenzacijo in relativno hitrost med fazama (model gonilnega toka) smo z uporabo lastnih FORTRAN-skih podprogramov [17] vključili v sedanji program RELAP5/MOD3.2.2 Gamma.

Izračune s spremenjenim programom (označenim z RELAP5_new) smo primerjali z izračuni s sedanjim programom (označenim z RELAP5_old) in z nizkotlačnimi preizkusi podhlajenega vrenja iz literature ([1] do [4]). Obratovalne razmere obravnavanih preizkusov so podane v preglednici 1. Preizkusi Zeitouna in Shoukrija ([1] in [2]) ter Donevskega in Shoukrija [3] so bili izvedeni v 306 mm dolgi greti cevi kolobarjastega prečnega prereza z notranjim premerom 13 mm in zunanjim premerom 25 mm. Testna sekcija Dimmicka in Selanderja [4] je bila 308 mm dolga cev z greto steno notranjega premera 12,3 mm. Za vsak preizkus smo razvili vhodni

3 RESULTS AND DISCUSSION

The net amount of vapour in the channel during sub-cooled flow boiling depends on the interaction between the wall evaporation, the condensation and the relative velocity of the bubbles with regard to the liquid. As this paper focuses on wall-evaporation modelling, the details about the modelling of other mechanisms are not provided; however, they can be found in [16]. The set of closure relations for the wall evaporation, the condensation and the relative velocity between phases (drift-flux model) was incorporated into the current code RELAP5/MOD3.2.2 Gamma via our own FORTRAN subroutines [17].

The calculations with the modified code (denoted as RELAP5_new) were compared with the existing code calculations (denoted as RELAP5_old) and against low-pressure sub-cooled boiling experiments from the literature ([1] to [4]). The operating conditions of the experiments are given in Table 1. The experiments of Zeitoun and Shoukri ([1] and [2]) and Donevski and Shoukri [3] were performed in a 306-mm-long heated annulus with inner and outer diameters of 13 mm and 25 mm, respectively. The test section of Dimmick and Selander [4] was a 308-mm-long cylindrical tube with a heated wall, having an inner diameter of 12.3 mm. An input model was developed for each

Preglednica 1. *Obratovalne razmere pri preizkusih*
Table 1. *Operating conditions of the experiments*

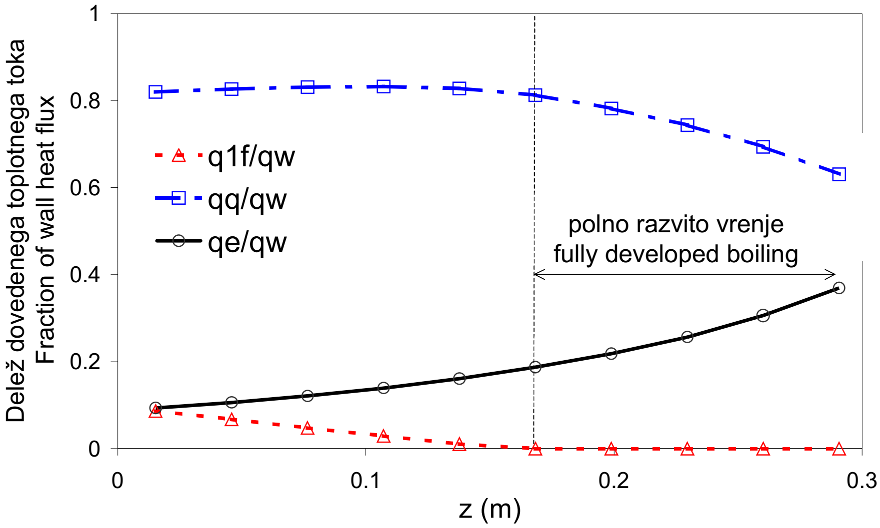
Vir Reference	Št. preiz. Exp. No.	q_w kW/m^2	G kg/m^{2}s	p_{in} bar	$\Delta T_{sub,in}$ ^{o}C
[1]	1	213,6	161,2	1,14	13,1
	2	480	208,1	1,14	20
[2]	3	508	264,1	1,5	16,8
	4	596	263,8	1,2	20,1
[3]	5	586,4	315,1	2,11	23,7
	6	481,4	392,1	1,54	18,5
[4]	7	805	620,2	1,65	44,3
	8	472	630,7	1,65	27,5

model, kjer smo definirali geometrijsko obliko testne sekcije, robne pogoje in diskretizacijo računskega območja [17].

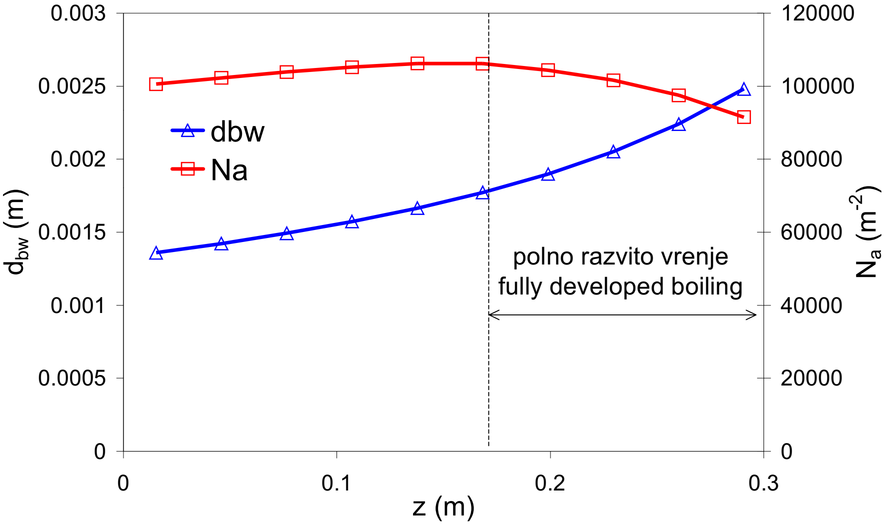
Na slikah 2 in 3 so predstavljeni značilni parametri novega modela stenskega uparjanja. S spremenjenim programom smo simulirali preizkus št.1 (preglednica 1). Na sliki 2 je predstavljena razdelitev dovedenega toplotnega toka vzdolž kanala. Vidimo lahko, da se enofazni konvekcijski toplotni tok $q_{1\phi}$ zmanjšuje, predvsem na račun večanja uparjalnega toplotnega toka q_e. Največji delež dovedenega toplotnega toka se prenaša na podhlajeno kapljevino zaradi površinskega hlajenja q_Q. Območje »*polno razvitega vrenja*«, kjer je $q_{1\phi}=0$, dosežemo približno na polovici gretega dela kanala. V tem območju vplivno območje mehurčkov pokriva celotno greto površino (A_{bub} =1). Kakor je prikazano na sliki 3, se premer mehurčka d_{bw} zvečuje vzdolž kanala, kar je v

experiment, where the test-section geometry, the boundary conditions and the discretization of the computational domain were defined [17].

Figs. 2 and 3 present the characteristic parameters of the new wall-evaporation model. Experiment No.1 (Table 1) was simulated with the modified code. Fig. 2 presents the partitioning of the wall heat flux along the heated channel. As can be seen, the single-phase convection heat flux, $q_{1\phi}$, decreases, mostly on account of the increasing of the evaporation heat-flux component, q_e. Most of the wall heat flux is transferred to the sub-cooled liquid as a result of quenching, q_Q. A "*fully developed boiling*" region, with $q_{1\phi}=0$, is reached approximately halfway along the heated channel. In this region, the bubble influence area covers the entire heated surface (A_{bub} =1). As shown in Fig. 3, the bubble diameter, d_{bw}, increases along the channel, which is in accordance



Sl. 2. *Izračunana porazdelitev dovedenega toplotnega toka vzdolž kanala (primer 1, preglednica 1)*
Fig. 2. *Calculated partitioning of the wall heat flux along the channel (Case 1, Table 1)*



Sl. 3. *Izračunani razvoj premera mehurčka d_{bw} in gostote aktivnih nukleacijskih jeder N_a vzdolž kanala (primer 1, preglednica 1)*

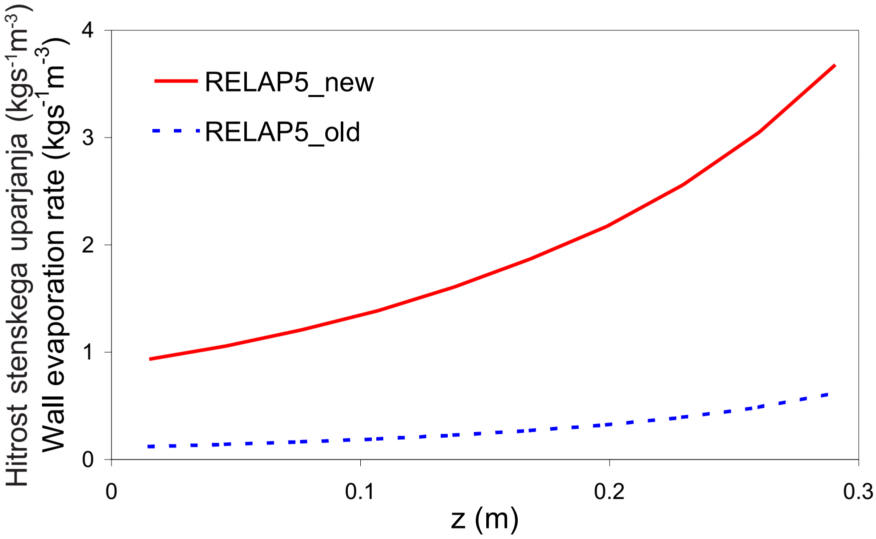
Fig. 3. *Calculated evolution of the bubble diameter, d_{bw}, and the density of the active nucleation sites, N_a, along the channel (Case 1, Table 1)*

skladu s preizkusnimi opažanji [2]. Gostota nukleacijskih jeder N_a se počasi zvečuje v območju »*delno razvitega vrenja* « (A_{bub}<1), medtem ko se začne zmanjševati v območju *polno razvitega vrenja* zaradi nadaljnjega večanja premera mehurčka d_{bw}.

Na sliki 4 je za preizkusni primer 1 prikazana primerjava hitrosti stenskega uparjanja, izračunanih s spremenjenim (RELAP5_new) in sedanjim programom (RELAP5_old). Kakor vidimo, so hitrosti stenskega uparjanja bistveno višje v primeru spremenjenega programa.

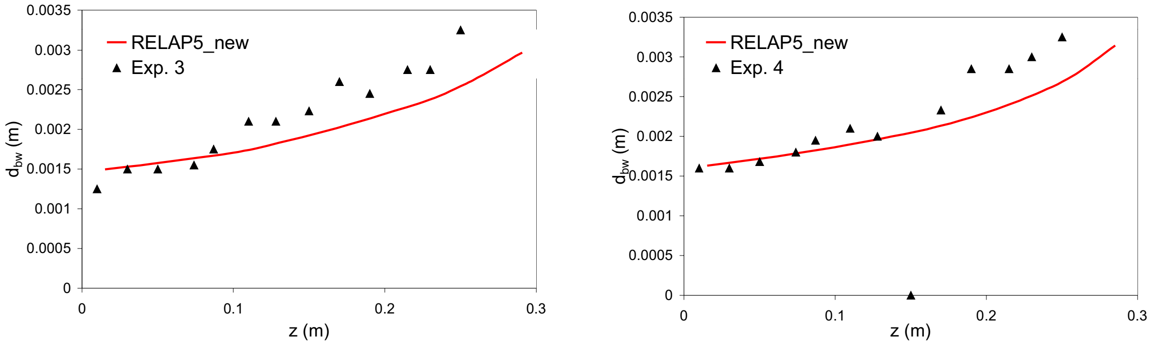
with experimental observations [2]. The nucleation site density, N_a, slowly increases in the "*partially developed boiling*" region (A_{bub}<1), whereas it starts decreasing in the *fully developed boiling region* due to a further increase in the bubble diameter, d_{bw}.

In Fig. 4, the wall-evaporation rates calculated by the modified (RELAP5_new) and the existing codes (RELAP5_old) are compared for the same experimental case 1. As can be seen, the wall-evaporation rates are significantly higher in the case of the modified code calculation.



Sl. 4. *Izračunane hitrosti stenskega uparjanja vzdolž kanala (primer 1, preglednica 1)*

Fig. 4. *Calculated wall-evaporation rates along the channel (case 1, Table 1)*



Sl. 5. *Izračunane in izmerjene [2] vrednosti premera mehurčka vzdolž kanala (primera 3 in 4, preglednica 1)*

Fig. 5. *Calculated and measured [2] values of the bubble diameter along the channel (cases 3 and 4, Table 1)*

Preglednica 2. *Izmerjene ([1] in [2]) in izračunane (RELAP5_new) vrednosti povprečne temperature stene*

Table 2. *Measured ([1] and [2]) and calculated (RELAP5_new) values of the average wall temperature*

Št. preiz. Exp. No.	$T_{w,exp}$ K	$T_{w,calc}$ (RELAP5_new) K	$(T_{w,calc} - T_{w,exp})\times100/T_{w,exp}$ %
1	393,0	391,8	-0,3
2	400,0	400,1	0,025
3	410,5	410,0	-0,12
4	406,3	407,0	0,17

Ker preizkusnih podatkov o gostoti aktivnih nukleacijskih jeder ni na voljo, smo izračun N_a preverili posredno, s primerjavo izračunanih in izmerjenih vrednosti premera mehurčka in temperature stene. Po en. (11) je gostota aktivnih nukleacijskih jeder odvisna od premera mehurčka in temperature stene. Kakor je prikazano na sliki 5, izračun s spremenjenim programom RELAP5 razmeroma dobro napove izmerjene [2] vrednosti premera mehurčka (povprečene po prerezu kanala).

V preglednici 2 so za 4 preizkusne primere (preglednica 1) podane izmerjene in izračunane vrednosti temperature grete stene. Za vsak preizkusni primer je podana ena vrednost, ki pomeni temperaturo povprečeno po celotni notranji površini grete stene. Povprečenje je smiselno, saj so tako izmerjene kakor izračunane temperaturne porazdelitve vzdolž kanala skoraj nespremenjene. Kakor je prikazano v preglednici 2, je tudi ujemanje izmerjenih in izračunanih temperatur sten zelo dobro.

Celotni model podhlajenega vrenja sestoji iz posameznih podmodelov, ki vplivajo na izračun deleža pare v gretem kanalu. Poleg modela stenskega uparjanja sta najpomembnejša model kondenzacije in model gonilnega toka. Da bi zaupali izračunu hitrosti stenskega uparjanja, smo preverili

As the experimental data on the nucleation site density, N_a, are not available, the calculation of N_a was validated indirectly, by comparing the calculated bubble diameter and the wall temperature with the experimental values. According to Eq. (11), the active nucleation site density depends on the bubble diameter size and on the wall temperature. As shown in Fig. 5, the measured [2] bubble diameter values (averaged over the channel cross-section) are reasonably well predicted by the modified RELAP5 calculation.

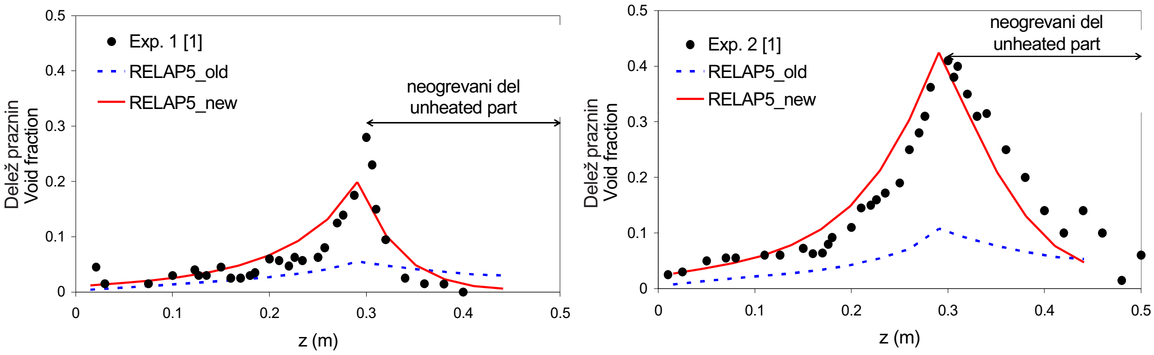
Table 2 provides measured and calculated values of the heated wall temperature for four experimental cases (Table 1). For each experimental case, one value is provided, representing the temperature averaged over the entire inner surface of the heated wall. The averaging is reasonable since both the measured and calculated temperature distributions along the channel are almost constant. As presented in Table 2, very good agreement between the measured and calculated wall temperatures is also obtained.

The overall sub-cooled boiling model consists of several sub-models that influence the calculation of the vapour content in the heated channel, [16]. Besides the wall-evaporation model, the condensation model and the drift-flux model are the most important. To have confidence in the wall-evaporation rate calculation, tudi ta dva modela. Na sliki 6 je prikazana primerjava izračunanih in izmerjenih [1] porazdelitev deleža parne faze v gretem in v neogrevanem delu navpičnega kanala. V gretem delu kanala na delež parne faze vplivata stensko uparjanje in kondenzacija, medtem ko v neogrevanem delu kanala poteka le kondenzacija parnih mehurčkov, zato se delež parne faze hitro zmanjšuje vzdolž kanala. Izračuni s spremenjenim programom (RELAP5_new) se dobro ujemajo z izmerjenim manjšanjem deleža parne faze in potrjujejo, da je bil uporabljen ustrezen model kondenzacije. V primeru izračunov s sedanjim programom (RELAP5_old) so vrednosti deleža parne faze bistveno nižje vzdolž celotne dolžine kanala, predvsem zaradi premajhne generacije pare ob steni. V neogrevanem delu kanala je nagib manjšanja deleža parne faze manj strm kakor v preizkusu, kar kaže na prenizko hitrost kondenzacije. Spremenjeni program RELAP5 (RELAP5_new) vključuje tudi novi model gonilnega toka [16], ki določa relativno hitrost med fazama. Primerjava izračunanih relativnih hitrosti z izmerjenimi vrednostmi je pokazala dobro ujemanje v primeru izračunov s spremenjenim programom, medtem ko je sedanji program (RELAP5_old) napovedal prevelike relativne hitrosti [16].

Na sliki 7 je prikazana primerjava izračunanih (RELAP5_old in RELAP5_new) in izmerjenih deležev parne faze vzdolž gretega kanala. Večja hitrost stenskega uparjanja v primeru izračuna RELAP5_new vpliva na večji delež pare v kanalu. Izračuni s sedanjim programom napovejo precej manjši delež parne faze od izmerjenega, medtem ko se izračuni s spremenjenim programom dobro ujemajo z izmerjenimi vrednostmi.

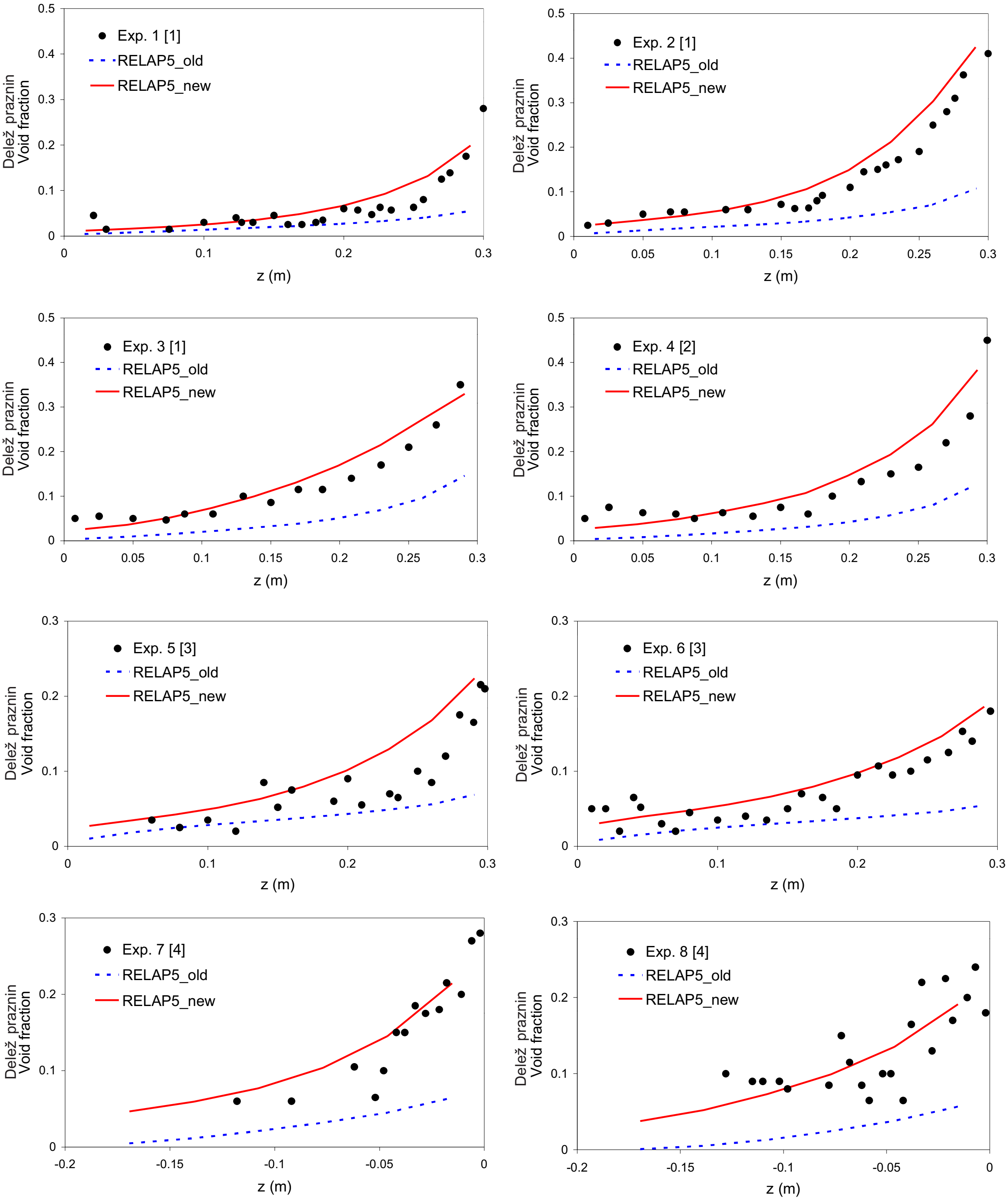
these two models were also validated. In Fig. 6. a comparison of the calculated and measured [1] void-fraction distributions in the heated and unheated parts of the vertical channel is presented. In the heated part of the channel both the wall evaporation and the condensation have an influence on the void fraction, whereas in the unheated part of the channel only the condensation of vapour bubbles is present, causing the void fraction to decrease rapidly along the channel. The modified code calculations (RELAP5_new) agree well with the measured void-fraction decrease and confirm that an appropriate condensation model was used. The void-fraction values along the entire length of the channel are significantly lower in the case of the existing code calculations (RELAP5_old), mostly due to the vapour generation near the wall being too low. The slope of the void-fraction decrease in the unheated part of the channel is less steep, as in the experiment, which indicates a condensation rate that is too low. The modified RELAP5 code (RELAP5_new) also includes a new drift-flux model [16], which determines the relative velocity between the phases. A comparison of the calculated and measured values shows good agreement in the case of modified code calculations, whereas the existing code (RELAP5_old) predicted relative velocities that were too high [16].

A comparison of the calculated (RELAP5_old and RELAP5_new) and the measured void fractions in the heated channels is presented in Fig. 7. A higher wall-evaporation rate in the case of the RELAP5_new calculations leads to higher vapour contents in the channel. The existing code calculations significantly under-predict the measured void fraction, whereas the calculations with the modified code show good agreement with the measured values.



Sl. 6. *Izračunane in izmerjene [1] porazdelitve deleža parne faze v gretem in neogrevanem delu kanala (primera 1 in 2, preglednica 1)*

Fig. 6. *Calculated and measured [1] void-fraction distributions in the heated and unheated parts of the channel (Cases 1 and 2, Table 1)*



Sl. 7. *Primerjava vzdolžnih porazdelitev deležev parne faze*
Fig. 7. *Comparison of the axial void-fraction distributions*

4 SKLEPI

Z namenom, da bi razširili uporabnost termohidravličnih programov v območje nizkotlačnega podhlajenega vrenja, smo razvili model

4 CONCLUSIONS

To extend the range of applicability of the thermal-hydraulic codes to low-pressure sub-cooled boiling, a wall-evaporation model consistent with stenskega uparjanja, ki je skladen z osnovnimi mehanizmi nukleacije mehurčkov na greti steni. Model upošteva delitev dovedenega toplotnega toka na delež, ki se porabi za generacijo pare in delež, ki se porabi za segrevanje kapljevine. Model je tudi zmožen napovedati prehod iz delno razvitega v polno razvito območje podhlajenega vrenja.

Novi model stenskega uparjanja smo vključili v program RELAP5. Spremenjeni program RELAP5 poleg novega modela stenskega uparjanja vključuje tudi nova modela kondenzacije in gonilnega toka, ki vsi skupaj vplivajo na delež parne faze pri podhlajenem vrenju toka. Spremenjeni program smo preverili na vrsti nizkotlačnih preizkusov podhlajenega vrenja. Dosegli smo zelo dobro ujemanje izračunanih in izmerjenih deležev parne faze vzdolž kanala. Nasprotno je sedanji program napovedal bistveno premajhen delež parne faze pri vseh obravnavanih preizkusih.

the basic physical mechanisms of bubble nucleation on a heated wall has been developed. The model considers the decomposition of the wall heat flux into vapour-generation and liquid-heating parts, and is able to predict the transition from the partially developed to the fully developed sub-cooled boiling region.

The new wall-evaporation model was incorporated into the RELAP5 code. Besides the new wall-evaporation model, the modified RELAP5 code also includes new models for condensation and drift-flux, which altogether influence on the void fraction during sub-cooled flow boiling. The modified code was verified against a series of low-pressure sub-cooled boiling experiments. Very good agreement between the calculated and measured void fractions along the channel was achieved. In contrast, the existing code significantly under-predicts the void-fraction data in all the experiments.

5 SPREMENLJIVKE
5 NOMENCLATURE

pospešek navidezne mase	a_{VM}	m/s^2	acceleration due to virtual mass
prerez	A	m^2	cross-section
greta površina	A_w	m^2	heated area
specifična toplota kapljevine	c_{pl}	J/kgK	liquid specific heat
koeficient medfaznega trenja	C_i		interfacial drag coefficient
koeficient navidezne mase	C_{VM}		virtual mass coefficient
premer mehurčka, ki nastane na steni	d_{bw}	m	bubble diameter generated on the wall
hidravlični premer kanala	D_e	m	channel equivalent diameter
specifična notranja energija	e	J/kg	specific internal energy
težnostni pospešek	g	m/s^2	acceleration due to gravity
masni pretok	G	kg/m^{2}s	mass flux
specifična entalpija	h	J/kg	specific enthalpy
uparjalna toplota	h_{lg}	J/kg	latent heat
toplotna prevodnost kapljevine	k_l	W/mK	liquid thermal conductivity
Nusseltovo število = $q_w D_e/k_l$	Nu		Nusselt number = $q_w D_e/k_l$
tlak	p	Pa, bar	pressure
Pecletovo število = $GD_e c_{p,l}/k_l$	Pe		Peclet number = $GD_e c_{p,l}/k_l$
Prandtlovo število kapljevine	Pr_l		liquid Prandtl number
površinski toplotni tok	q	W/m^2	surface heat flux
vir toplote na enoto prostornine	Q	W/m^3	heat source per unit volume
Reynoldsovo število toka = GD_e/m	Re		Reynolds flow number = GD_e/μ
Stantonovo število = $Nu/RePr_l$	St		Stanton number = $Nu/RePr_l$
temperatura	T	K	temperature
hitrost	v	m/s	velocity
nadzorna prostornina	V	m^3	control volume
relativna hitrost med fazama	v_r	m/s	relative velocity between phases
Grške črke			*Greek symbols*
prostorninski delež faze k	α_k		volume fraction of phase k

hitrost prenosa mase	Γ	kg/sm^3	mass transfer rate
dinamična viskoznost kapljevine	μ_l	Pa s	liquid viscosity
gostota	ρ	kg/m^3	density
Spodnji indeksi			*Subscripts*
od meje faz proti fazi *k*	ik		from interface to phase *k*
vstopni pogoji	in		inlet conditions
kapljevina	l		liquid
para	g		vapour
faza *k*	k		phase *k*
nasičenje	sat		saturation
podhlajeno	sub		sub-cooling
stena	w		wall
od stene proti fazi *k*	wk		from wall to phase *k*

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