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Meritve tokovnega polja okrog osamljenega mehurja pare nad umetno ustvarjenim zarodnim mestom s tehniko meritve hitrosti s sliko sledilnih delcev

Velocity-Field Measurements Around an Isolated Vapour Bubble Over an Artificially Produced Nucleation Site Using the Particle Image Velocimetry Technique

Sanib Bašič - Jure Marn - Leopold Škerget

V prispevku smo podali izsledke fizikalnih meritev hitrostnega polja v območju nad zarodnim mestom, ki je dejavno med potekom mehurčastega naravno konvektivnega vrenja. Po predstavitvi temeljnih mehanizmov prenosa v preučevanem režimu vrenja smo določili vodilne cilje potekajoče raziskave, opisali merilno progo ter podali nekatere osnovne značilnosti merilne tehnike MHSSD. Opisali smo potek meritev tokovnega polja, strnili rezultate preizkusa, nato pa povzeli sklepne ugotovitve. Delo prispeva h kolikostnem vrednotenju konvektivnih učinkov med oddaljevanjem parnih mehurjev od vrelne ploščice po ločitvi od zarodnega mesta.

(Ključne besede: vrenje mehurčkasto, zakonitosti fizikalne, tehnika merilna, polja tokovna)

In this paper measurements of the velocity field in the region over a nucleation site that was active during nucleate pool boiling are presented. After the presentation of the principal transport mechanisms in the investigated boiling regime the main aims of the research are defined. The experimental rig is presented and some basic features of the PIV measurement technique are described. A procedure for flow-field measurements is described, the results are presented and we conclude with final statements. The work contributes to a quantitative determination of the convective effects during the vapour-bubble removal process on heating a wafer after departure from a nucleation site.

(Keywords: nucleate boiling, vapour bubbles, hydrodynamics, experimental techniques, flow fields)

0 UVOD

Delo, ki ga predstavljamo v pričujočem prispevku, je posvečeno preučevanju fizikalnih zakonitosti v režimu delno razvitega mehurčastega naravno konvektivnega vrenja. Slednje je definirano kot heterogena fazna preobrazba iz kapljevitega v plinasto agregatno stanje, ki poteka ob intenzivnem nastajanju osamljenih parnih mehurjev v netekoči kapljevini. Gonilna sila številnih študij na tem področju izvira zlasti iz dveh dejstev, in sicer: (a) med potekom nukleacijskega vrenja je mogoče doseči zelo velike vrednosti gostote toplotnega toka ob razmeroma majhnih vrednostih stenskega pregretja, s čimer je omogočeno izjemno učinkovito hlajenje grelnih površin, ter (b) dedna lastnost pojava je zmožnost shranjevanja velikih količin eksergije v obliki latentne toplote parne faze. Prva značilnost pojava se izrablja v številnih napravah strojne (uparjalniki, povrelniki,

0 INTRODUCTION

The aim of this paper is to provide some insight into the hydrodynamics of the bubbling process during the partly developed nucleate boiling regime. This can be defined as a heterogeneous phase transition from the liquid to the vapour state, accompanied by the intensive production of isolated bubbles in an initially quiescent liquid body. The main impetus of the numerous studies performed in this area arises primarily from two facts: (a) very high heat fluxes at relatively low values of wall superheating can be achieved during the nucleate boiling process, and due to this a very effective cooling of heated surfaces is achieved employing this modus of heat transfer; and (b) an inherent feature of the boiling phenomenon is that a vast amount of energy can be compactly stored as the latent heat of vapour phase, and afterwards it can be readily hladilniki itn.) in elektronske (procesorske enote, tiskana vezja itn.) industrije, medtem ko je druga pogostokrat izkoriščena kot ena izmed stopenj pri spremembi energije v energetskih postrojih (parni kotli in uparjalniki termoelektrarn).

Ključni motiv preučevanja različnih režimov vrenja je, v nasprotju z zapletenostjo in navidezno naključnostjo samega pojava, preprost. Smiselno bi bilo izpeljati takšne matematične izraze za gostoto toplotnega toka, ki bi znotraj sprejemljive natančnosti zadovoljili inženirsko prakso in bi ne bili odvisni od velikega števila geometrijskih in postopkovnih parametrov, kar se zelo pogosto dogaja ob uporabi znanih izkustvenih korelacij. Tudi dandanes ni redkost, da se vrednosti gostote toplotnega toka, ki je določena na podlagi več različnih, sicer uveljavljenih izkustvenih korelacij, razlikujejo celo za več ko 200 odstotkov glede na eksperimentalno ugotovljeno vrednost [1].

S pospešenim razvojem fizikalnih meritev in intenzivnim kopičenjem eksperimentalnih podatkov se pojavljajo prvi fenomenološki (mehanistični) modeli prenosa toplote v režimu mehurčastega vrenja. Kljub vloženim naporom znanosti še ni uspelo podati veljavnega analitičnega modela za vrednotenje prenosa toplote, celo v režimu osamljenih mehurčkov, brez uporabe empirično določenih stalnic, s čimer se uporabnost razvitih modelov močno omejuje. Različni mehanistični modeli so tako dopolnjeni z eksperimentalnimi stalnicami in predstavljajo bolj ali manj znane polempirične korelacije prenosa toplote.

1 VODILNI MEHANIZMI PRENOSA V REŽIMU MEHURČASTEGA VRENJA

V splošnem obstaja okvirno soglasje, da so vodilni mehanizmi, ki prispevajo k prenosu toplote v režimu delno razvitega mehurčastega naravno konvektivnega vrenja: (a) mikrokonvektivni učinki med potekom rasti (sl. 1a), ločevanja (sl. 1b) in oddaljevanja mehurčkov (sl. 1c) [2]; (b) prehodni prevod toplote s spremembo “makro“ mejne plasti nad grelno površino, ki poteka med inkubacijsko dobo (sl. 1d); (c) izparevanje adsorbirane “mikro“’ plasti kapljevine pod rastočim mehurčkom in vzdolž medfazne površine (sl. 1e) in (d) naravna konvekcija, ki prevladuje v področjih zunaj vpliva posameznih zarodnih mest (sl. 1f) [3]. Štirje mehanizmi potekajo hkrati, njihov relativni pomen in prispevek k skupnemu toplotnemu toku pa je zelo odvisen od sistemskih in obratovalnih razmer. Pravilno vrednotenje pomembnosti posameznega izmed omenjenih mehanizmov ostaja še vedno odprto vprašanje.

Uveljavljeni model prenosa toplote s štirimi vodilnimi mehanizmi je še vedno idealizacija dejanskih razmer, kajti ta velja le hipotetično ob mehurjenju z osamljenega zarodnega mesta.

recovered in another process. The first feature is frequently used in apparatus in the process (evaporators, reboilers, coolers, etc.) and electronic (processor units, printed circuits, etc.) industries, while another one is often applied as one of the stages in energy-conversion systems (e.g., boilers and vapour generators in fossil-fuel power plants).

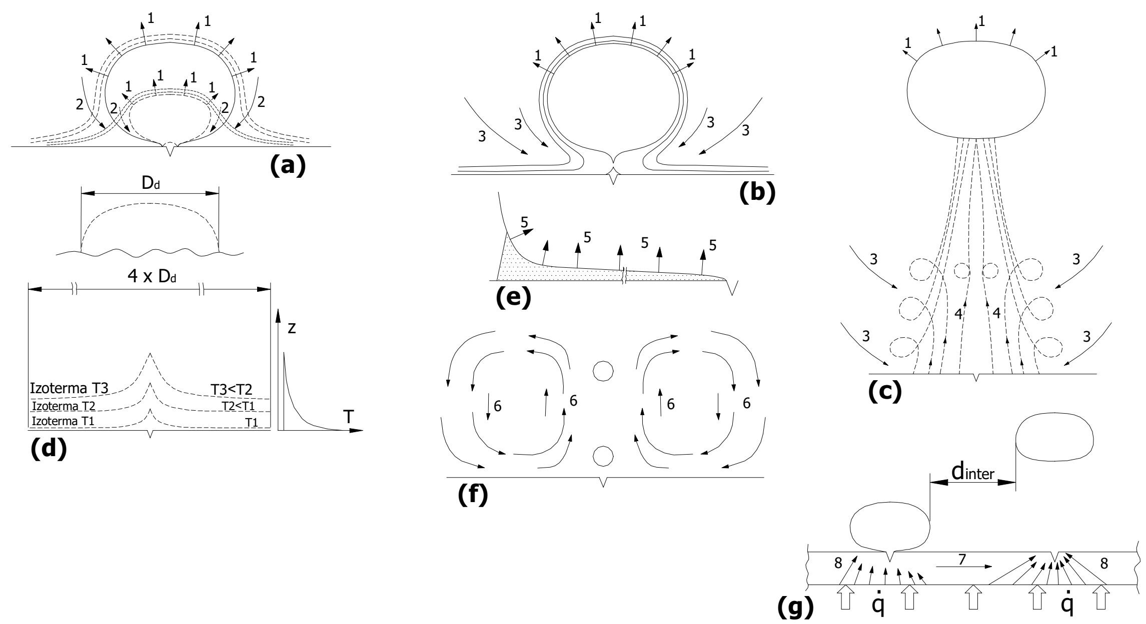
In spite of the complexity of the boiling phenomenon, a leading motive, and also the main goal of investigations concerning different boiling regimes, is very simple. Namely, suitable mathematical expressions for the mean heat flux are needed with acceptable accuracy satisfy engineering practice in such a way that they should not depend on many geometrical and process parameters. Even today, it is not unusual for the values of the heat flux estimated on the basis of different well-known empirical correlations to differ by more than 200% from experimental values [1].

As a result of the fast development in the area of experimental techniques and intensive data accumulation the first phenomenological (mechanistic) models of heat transfer in the bubble boiling regime have been established. In spite of many efforts the scientific community has not yet achieved an appropriate analytical model for heat-transfer prediction that is free of empirical constants, even in the regime of isolated bubbles. With this limitation the usefulness of developed models is much restricted. Thus, the different mechanistic models use experimental constants and present more-or-less known semi-empirical correlations of heat transfer.

1 GOVERNING TRANSPORT MECHANISMS IN THE NUCLEATE BOILING REGIME

It is well established that the governing transport mechanisms contributing to the heat transfer in the regime of partially developed nucleate boiling are: (a) micro-convection during the growth (Fig. 1.a), the departure (Fig. 1.b) and the rising (Fig. 1.c) of the bubbles [2], (b) transient heat conduction during the reformation of the macro-boundary layer immediately above the heating surface (Fig. 1.d), which occurs during the waiting period, (c) evaporation of the adsorbed liquid micro-layer underneath the growing bubble and around the bubble interface (Fig. 1.e), and (d) natural convection that is dominant out of the regions affected by the activity of nucleation sites (Fig. 1.f) [3]. Four mechanisms take place simultaneously and their relative contribution to the overall heat transfer depends to a great extent on the system and the operational parameters. The correct prediction for these particular mechanisms still remains an open question.

The proposed heat-transfer model with four governing mechanisms can be viewed only as an idealised description of the real situation because of



1 - odrivanje makro plasti pred svodom mehurja
2 - stransko obtekanje mehurja
3 - zalitje vrelne površine
4 - sesalni učinek in vrtinčenje v tokovni brazdi
5 - izparevanje na medfazni površini
6 - polje naravne konvekcije
7 - stranski prevod toplote
8 - toplotni tok skozi vrelno ploščo

1 - macro layer removal in front of bubble cap
2 - lateral flows around bubble
3 - recovering of boiling surface
4 - suction effects and flow wake formation
5 - vaporization at bubble interface
6 - natural convection flow field
7 - lateral heat conduction
8 - heat flow through heating plate

Sl. 1. *Vodilni mehanizmi prenosa toplote v režimu mehurčastega vrenja: (a) ekspanzija, (b) ločitev, (c) oddaljevanje mehurja in sesalni učinek, (d) prehodna sprememba makromejne plasti, (e) uparjanje mikromejne plasti, (f) prosta konvekcija, (g) interakcija nukleacijskih mest*

Fig. 1. *Governing transport mechanisms in the partial nucleate boiling regime: (a) expansion, (b) separation, (c) bubble raising and the suction effect, (d) transient reformation of the macro-boundary layer, (e) micro-boundary-layer evaporation, (f) natural convection, (g) interaction between nucleation sites*

Medsebojne interakcije zarodnih mest (sl. 1g) [4] vnašajo dodatne mehanizme (proženje in deaktivacija zarodkov, sekundarna nukleacija itn.), katerih vrednotenje je ozko povezano z mikrostanjem vrelne površine (krajevno-časovna porazdelitev, omočljivost, velikost ter oblika potencialnih zarodnih mest) in pomenijo dodatno neznanko v postopku mehurčastega vrenja.

V režimu osamljenih parnih mehurjev sta mikrokonvekcija in prehodni prevod toplote v kapljevini v neposredni bližini vrelne površine najbolj pomembna mehanizma prenosa toplote. Po sprožitvi vrenja je pregreta mejna plast vsakokrat potisnjena navzven in premešana s hladnejšo okoliško kapljevino. Mehurji delujejo kot neke vrste mikro črpalke, s čimer hladnejšo kapljevino potiskajo stran od površine, nadomešča jo pa hladnejša kapljevina iz višje ležečih plasti. Ta mehanizem sta prvič predlagala Forster in Greif [5]. S seštevanjem prispevkov prehodnega prevoda toplote nad zarodnim mestom in okrog njega, izparevanja mikromejne plasti pod mehurjem ter naravne konvekcije v področjih zunaj

the fact that it holds merely for a single nucleation site. Mutual interactions between statistically arranged nucleation sites on a real surface (Fig. 1.g) [4] bring about additional mechanisms (activation and deactivation of cavities, secondary nucleation, etc.), which strongly depend on the microstate of the boiling surface (spatio-temporal distribution, wettability, size and shape of potential nucleation sites) and it is additionally unknown in the process of bubble boiling.

In the isolated bubble regime, micro-convection and transient conduction into the liquid adjacent to the wall are probably the most important mechanisms for heat removal from an upward-facing horizontal surface. After bubble inception, the superheated liquid layer is pushed outwards and mixes with the bulk liquid. The bubble acts like a pump in removing the hot liquid from the surface and replacing it with cold liquid. This mechanism was originally proposed by Foster and Greif [5]. Combining the contribution of transient conduction on and around nucleation sites, the micro-layer evaporation underneath the bubbles and the natural vpliva zarodnih mest, pridemo do izraza za srednjo vrednost gostote toplotnega toka v režimu delno razvitega mehurčastega vrenja:

convection on inactive areas of the heater, expressions for partial nucleate boiling heat flux are obtained as:

$$\dot{q} = \underbrace{\left(N_a \pi D_d^{\,2} K/4\right)\dot{q}_{tc}}_{\substack{\text{prehodni prevod toplote} \\ \text{transient heat conduction}}} + \underbrace{\left(1 - N_a \pi D_d^{\,2} K/4\right)\dot{q}_{nc}}_{\substack{\text{naravna konvekcija} \\ \text{natural convection}}} + \underbrace{\left(N_a \pi D_d^{\,2}/4\right)\dot{q}_{ev}}_{\substack{\text{izparjanje mikro plasti} \\ \text{micro-layer evaporation}}} \qquad (1)$$

$$\dot{q} = \underbrace{\underbrace{\frac{K^2}{2}\sqrt{\pi(\lambda\rho c_p)_l f}\, D_d^{\,2} N_a \Delta T + \left(1 - \frac{K^2}{2} N_a \pi D_d^{\,2}\right)\overline{\alpha}_{nc}\Delta T}_{[6]} + N_a \frac{\pi}{4} D_d^{\,2}\overline{\alpha}_{ev}\Delta T}_{[7]} \qquad (2).$$

Prva izmed členov v zgornji enačbi sta bila vključena v izvirnem modelu, ki sta ga predlagala Mikic in Rohsenow [6]. Izparevanje na medfazni površini sta zajela s prvim členom, ki predstavlja prehodni prevod toplote v kapljevini. Zadnji člen v enačbah (1) in (2), ki je dodan kot pomemben prispevek skupnemu toplotnemu toku, sta predlagala Judd in Hwang [7]. Ta člen upošteva izparevanje mikro plasti, ki nastaja med mehurjem in trdno površino. Simboli v zgornjih enačbah označujejo: N_a - gostoto delujočih zarodnih mest, D_d - premer mehurjev ob ločitvi, K - stalnico krajevnega vpliva nastajajočih mehurjev, $(\lambda\rho c_p)_l$ - zmnožek snovnih lastnosti kapljevite faze, f - frekvenco nastajanja mehurjev in $\overline{\alpha}$ - povprečno toplotno prestopnost ($\overline{\alpha}_{nc}$ za naravno konvekcijo, $\overline{\alpha}_{ev}$ za izparevanje mikro plasti). Iz enačb (1) in (2) je razvidno, da so mikrokonvektivni učinki mehurjenja zajeti le posredno, in sicer skozi vrednosti K, f in N_a.

Equation (2) arises from Equation (1) when expressions for heat fluxes for each of these mechanisms are inserted. Only the first two terms in the above equations were included in the original model proposed by Mikic and Rohsenow [6]. The evaporation at the bubble boundary is included in the first term, which represents the transient conduction in the liquid. The addition of the last term on the right-hand side of Equations (1) and (2) was suggested by Judd and Hwang [7]. This term accounts for the micro-layer evaporation at the base of the bubbles. For Equation (2) to serve as a predictive tool, the following must be known: the bubble diameter at departure D_d, the bubble release frequency f, the proportionality constant K for the bubble area of influence, the number density of active nucleation sites N_a and the average heat-transfer coefficient $\overline{\alpha}_{nc}$ and $\overline{\alpha}_{ev}$ for natural convection and micro-layer evaporation, respectively. From Equations (1) and (2) it is evident that the micro-convection contribution to the overall heat transfer is included only implicitly through the value of constants K, f and N_a.

2 CILJI RAZISKAVE

Cilj raziskave je kolikostno vrednotenje mikrokonvektivnih učinkov med rastjo, ločevanjem in oddaljevanjem (sesalni učinek) parnih mehurjev od vrelne površine (prvi med prej ponazorjenimi mehanizmi, sl. 1a-1c). Domnevamo namreč, da je prav konvektivni mehanizem prenosa toplote neustrezno ovrednoten in da ima večji pomen, kakor ga upoštevajo (ali sploh ne) do sedaj predlagani modeli prenosa toplote. Na začetku smo se omejili le na zasledovanje tokovnih razmer, ki so posledica mehurjenja z osamljenega umetno ustvarjenega zarodnega mesta. Umetno nastajanje zarodnih mest smo opravili z metodo mehanskega vtiskovanja na finopoliranih jeklenih ploščicah, s čimer smo odpravili možnost sleherne nukleacije na nezaželenih mestih. Z vpeljanim merilnim postopkom bo v prihodnje mogoče ovrednotiti tudi vpliv nekaj novo dodanih zarodnih mest na tokovno polje nad vrelno površino ter učinkovanje le-teh na skupni prenos toplote, upoštevaje interakcije med posameznimi zarodki.

Vodilni smoter opravljene začetne faze raziskovanja je bil: (a) zasnova in postavitev

2 AIMS OF THE INVESTIGATION

The distribution of velocity vectors in the flow fieled during the growth, the departure and the rising (suction effect) of vapours bubbles (mechanisms presented on Fig. 1.a-1.c) over the boiling surface is the main goal of the investigation reported in this paper. We suppose that the convective mechanism of heat transfer in boiling is not taken into consideration correctly till now (if at all) and that this phenomenon is more important than it has been proposed in known models of heat transfer. Initially, we have restricted our investigation to only one artificially produced nucleation site on the fine polished boiling plate. A method of mechanical impression is used to form this micro-cavity on the boiling surface. Doing this a controlled bubbling process has been achieved in a narrow range over the single micro-cavity. Furthermore, the hydrodynamics characteristics of the flow field over a few additional nucleation sites formed on the boiling surface and mutual interactions between these sites can be explored using this procedure.

The investigation discussed here was performed in two steps: (a) designing and mounting of preizkusne proge za nadzorovano nastajanje mehurjev pare v definiranem režimu vrenja, ki bo omogočila preučevanje pojava z uporabo merilnih tehnik HDVK (hitra digitalna video kamera), MHSSD (meritve hitrosti s sliko sledilnih delcev) in LDA (laserska Dopplerjeva anemometrija) ter (b) pridobitev začetnih izsledkov hitrostnega polja okrog osamljenih mehurjev z uporabo eksperimentalne metode MHSSD.

3 MERILNA PROGA

Merilna proga (sl. 2) obsega (I) eksperimentalno napravo z oljno kopeljo in (II) merilni sistem MHSSD. Segreto olje iz oljne kopeli (1) priteka v primarni zbiralnik (2), kjer je s pomočjo usmeritvene šobe (3) omogočeno enolično in nepretrgano oblivanje spodnje površine vrelne ploščice (4). Nato se s povratnim cevovodom (5) olje zbira v sekundarnem zbiralniku (6), od tod pa odteka nazaj v oljno kopel. Masni pretok olja iz oljne kopeli se krmili z elektromotorjem z nastavljivo močjo (7), h kateremu je prigrajena zobniška črpalka (8). Primarni potopni električni uporovni grelnik (9) segreva olje, izstopno temperaturo le-tega pa uravnava krmilna enota (10) s temperaturno sondo in digitalnim termostatom. Skozi steno nosilne prirobnice (11), tik pod vrelno ploščico, je speljan kanal za hladilno vodo (12), ki je namenjen za izločenje obrobnih zarodkov. Na pritrjevalnik grelne ploščice (13) je nameščena kvadratna steklena vrelna komora (14) z vizualizacijskimi odprtinami (15). Vrelna komora je z zgornje strani tesno zaprta s pokrovom (16), na katerem so sekundarni potopni električni grelnik (17), halogenski osvetljevalnik (18) ter oddušnika pare (19). Celotna preizkusna naprava je toplotno izolirana.

Utripni laser Nd: YAG (“Neodimium Doped Yttrium Aluminum Garnet“) (20) z dvema resonatorjema ustvarja zeleno navpično polarizirano svetlobno pahljačo in osvetljuje polje toka nad zarodnim mestom, ki je v središču vrelne ploščice. Digitalna video kamera (21) z zgradbo svetlobnega senzorja DSC (dvojne svetlobne celice) je nameščena pravokotno glede na osvetlitveno ravnino toka. Laser in kamera sistema MHSSD sta prek pripadajočih nadzornih enot (22, 23) povezana s središčno procesorsko enoto “FlowMap“ (24) [8]. Slednja je povezana z osebnim računalnikom (25), na katerem je z računalniško programsko opremo “FlowManager“ omogočeno vodenje in nadzor celotnega merilnega sistema ter zbiranje, vrednotenje in analiza rezultatov.

Preizkusno napravo za preučevanje bazenskega vrenja smo zasnovali [9] ob upoštevanju robnega pogoja nespremenljive temperature vrelne ploščice. Za nosilo uparjalne

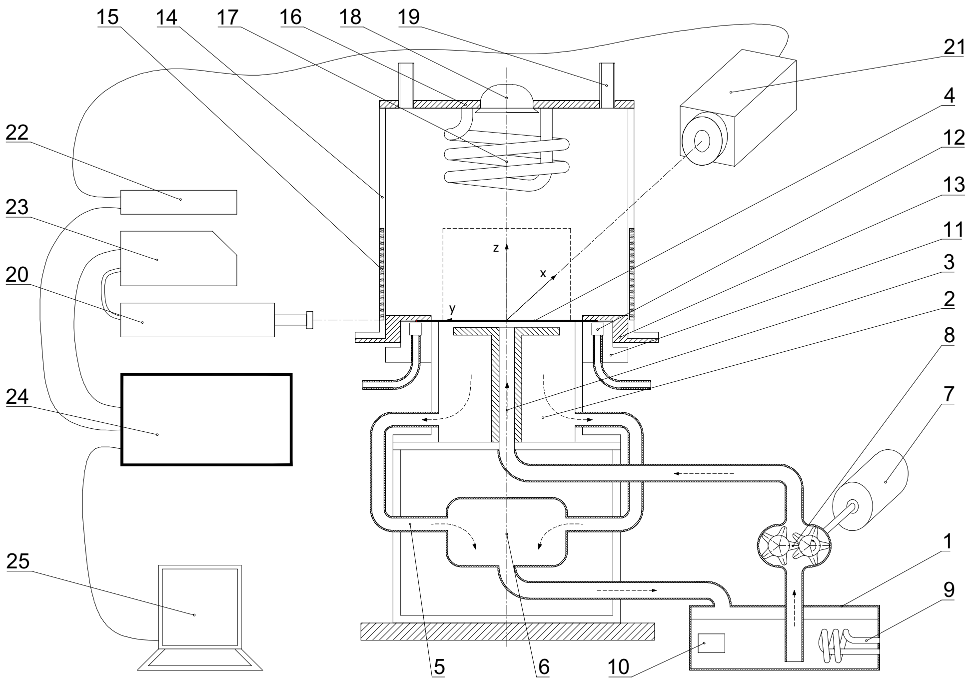
the experimental section, where the controlled production of vapour bubbles in a defined boiling regime can be maintained. Such a set-up has to be suitable for DHSVC (Digital High Speed Video Camera), PIV (Particle Image Velocimetry) and LDA (Laser Doppler Anemometry) measurement techniques, and (b) to obtain a preliminary velocity-field distribution around the isolated rising bubbles using the PIV technique.

3 EXPERIMENTAL SET-UP

The testing line (Fig. 2) consists of a (I) boiling vessel with an oil bath and (II) a PIV experimental system. The heating oil from the oil bath (1) is directed into the primary collector (2). A directing spout (3) serves to ensure a uniform and continuous spreading of the heating oil over the lower surface of the boiling plate (4). Through the return piping (5) and the secondary collector (6) the circulating oil is redirected back to the oil bath. An electromotor (7) with an adjustable rotational speed is connected to the gear oil pump (8). Thus, a mass flow rate of circulating oil can be changed in the required range. A primary electrical resistance heater (9) is immersed in the oil bath. The temperature sensor attached to this heater is connected to the control panel unit (10) ensuring precise temperature control throughout the experiment. Under the boiling plate through the wall of the supporting flange (11) a cooling-water channel (12) is formed, which is used to deactivate peripheral nucleation sites. A squarely formed boiling vessel (14) made from glass with four visualization openings (15) is mounted on the removable fixing flange (13). On the top of the boiling vessel a sealed cover with attached auxiliary equipment (16) is placed. These components are a secondary electrical heater for the water (17), halogenous lamp (18) and vapour vents (19). The boiling vessel is insulated to prevent heat losses to the surroundings.

A double-pulsed Nd:YAG (Neodimium-Doped Yttrium Aluminum Garnet) laser (20) with two separated exciting cavities produces a green, vertically polarised light sheet and illuminates the flow field over the nucleation site, which is situated in the central point of the boiling plate. The CCD (Charge Coupled Device) camera (21) with the PSI (Progressive Scan Interline) architecture of a light sensor is placed perpendicular to the illuminated plane of the flow field. With separated control units (22, 23) both the camera and the laser of the PIV system are connected to the central FlowMap processor unit (24) [8]. The latter is finally connected to a PC (25). An extra dedicated FlowManager program package is used here to manage and control the overall experimental system, enabling data acquisition, validation and analysis of results.

The experimental apparatus for the pool boiling investigation was designed [9] at the boundary condition of constant surface temperature along the heating plate. As the energy supply for the phase transition we used the internal caloric energy of the single-phase oil flow. The high heat capacity and the intensive flow rate of the circulating oil flowing along the lower side of small heating plate caused a negligible



Sl. 2. *Merilna proga (preizkusna naprava, oljna kopel, merilni sistem PIV)*
Fig. 2. *Experimental set-up (boiling vessel, oil bath, PIV measurement system)*

energije vode nad ploščico se uporablja notranja energija enofaznega toka segretega olja. Velika toplotna zmogljivost oljnega toka in kratkotrajen stik le-tega s ploščico miniaturnih izmer zagotavljata zanemarljive spremembe temperaturnega polja vzdolž vrelne ploščice. Glavna pomanjkljivost gretja z oljem tiči v: (1) problemih, ki so povezani s tesnjenjem oljne in vodne strani naprave in (2) potrebi po robustnejši gradnji, posledica česar so posebne osamitvene zahteve ter daljši prehodni pojav med zagonom preizkusa. Ob zasnovi preizkusne naprave, upoštevajoč robni pogoj nespremenljive gostote toplotnega toka, je mogoče ubežati vsem izmed omenjenih nevšečnosti, toda ta način je povezan z nekaj še bolj perečimi pomanjkljivostmi.

Z električnim uporovnim gretjem vrelne ploščice je namreč nemogoče doseči enakomerno porazdelitev gostote toplotnega toka vzdolž same ploščice. Znatne in težko izsledljive temperaturne spremembe v tem primeru močno vplivajo na ponovljivost sprožitve zarodnega mesta. Dokazano je bilo tudi to, da pojav elektromagnetnega valovanja v precejšnji meri vpliva na potek in ponovitve mehurjenja [3].

Ne glede na izbiro gretja je pri zasnovi preizkusne naprave treba: (1) zagotoviti najmanjši vizualizacijski vpadni kot kamere, (2) z uporabo ravnih steklenih površin omejiti morebitno raztresanje monokromatične laserske svetlobe, ki se kaže skozi lomne in odsevne učinke in (3) vpeljati hladilni sistem za deaktivacijo potencialnih zarodnih mest na robovih omočenega dela vrelne ploščice.

temperature variation of the boiling surface. The principle disadvantages of this heating-oil system are as follows: (1) it is necessary to ensure reliable sealing on both the water and the oil side of the boiling plate, and (2) the overall construction has to be more robust, which results in special insulating demands and causes a longer transition time from the cool state to the operational point at the saturation temperature. When designing experimental apparatus at constant-heat-flux boundary conditions over boiling surface, many of these weak points can be eliminated. However, this solution causes a variety of other problems, which have to be solved as well.

When electrical resistance heating is used as a boiling energy supply it is impossible to reach a uniform heat-flux distribution along the boiling surface. The intensive and undetectable temperature variations in this case affect the activity of the nucleation sites, which then become completely unstable. Furthermore, it was recognized recently that the electromagnetic field caused by electrical currents through the heating plate significantly affects the nucleation and bubbling process [10].

Irrespective of selected heating mode, the experimental apparatus has to satisfy the following demands: (1) the minimum visualization angle of the PIV camera in the measuring plane has to be ensured, (2) it is necessary to restrict the eventual dissipation of monochromatic light from the laser, which causes disturbing refraction and reflection effects, by using flat-glass windows, and (3) a cooling system for the deactivation of the peripheral nucleation sites on the boundaries of the boiling plate has to be built as a part of apparatus.

4 MERILNA TEHNIKA MHSSD

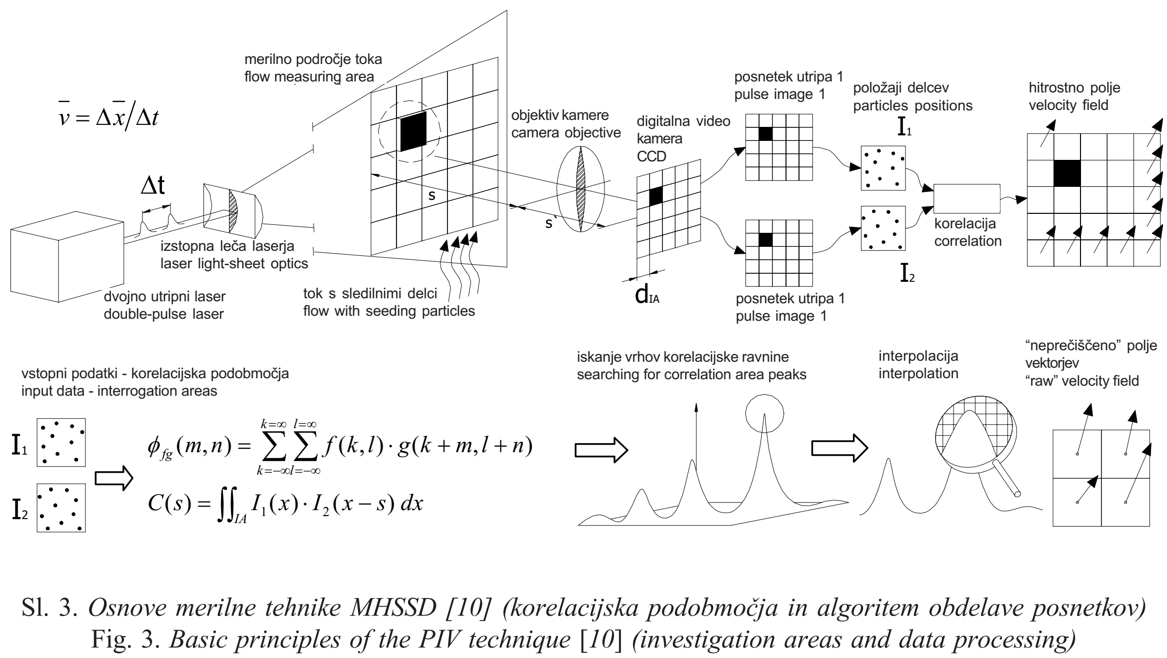
Kratica MHSSD označuje meritve hitrostnega polja s tehniko spremljanja osemenjevalnih delcev. Hitrostno polje tokovnega pojava se v izbrani merilni ravnini meri posredno na podlagi prepotovanih razdalj sledilnih delcev v določenem časovnem obdobju. Odboj laserske svetlobe na posameznih sledilnih delcih je s stroboskopskim učinkom ujet na časovno premaknjenem paru posnetkov MHSSD kamere. Celotno opazovano področje toka je nato razdeljeno na korelacijska podobmočja (sl. 3). Razsežnosti korelacijskega podobmočja določajo prostorsko resolucijo najmanjše sestave toka, katere vektor hitrosti se meri. S statistično metodo prečne korelacije se iščejo vrhovi korelacijske ravnine, ki se potem gladijo, z ustrezno interpolacijsko krivuljo pa se določi največja vrednost prečnokorelacijske funkcije. Položaj vrha v korelacijski ravnini neposredno ustreza povprečnemu vektorju premika sledilnih delcev znotraj obdelanega korelacijskega podobmočja [10]. Deljenje vektorja premika s časom med laserskima sunkoma definira hitrostni vektor. Kompozicija tako določenih vektorjev hitrosti čez vsa korelacijska podobmočja daje "neprečiščeno" hitrostno polje v merilni ravnini v točno določenem časovnem trenutku. Programska oprema na koncu omogoča odstranjevanje vseh čezmerno odstopajočih vektorjev.

Rezultat meritev MHSSD je časovno spremenljivo ravninsko hitrostno polje opazovanega področja. Za določitev tretje izmere vektorskega polja je potrebna posebna stereoskopska priprava. Pri merilni tehniki MHSSD je posebno pozornost treba nameniti ustrezni izbiri sledilnih delcev. Sedimentacijske in aglomeracijske lastnosti

4 PIV EXPERIMENTAL TECHNIQUE

PIV is the experimental method used for velocity-field measurement by tracing the seeding particles artificially added to a carrier fluid. The velocity distribution in the flow field is measured indirectly on the basis of the spatial displacement of groups of seeding particles in a defined time period. Laser-light reflection resulting from individual particles illuminated in the visualization plane is captured by a stroboscopic effect on temporally delayed image pairs of the PIV camera. During the PIV image processing a visualized region of flow is divided into the interrogation areas (Fig. 3). The spatial resolution of the smallest flow structure for which we want to measure the velocity vector is defined with the dimensions of the interrogation area. A statistical method of cross-correlation is then used to find a few of the highest peaks in the correlation plane. These maximum peaks are refined by a smoothing algorithm, and using suitable interpolation curves the maximum values of the cross-correlation function are determined. The maximum peak position in the correlation plane gives us directly a mean displacement vector of the seeding particles inside the considered interrogation area [10]. Dividing the displacement vector by the time between the successively delayed images defines the velocity vector. The combination of the resulting velocity vectors for each interrogation area presents a raw velocity field in the testing plane in a defined time.

The results of the PIV measurement protocol are the unsteady planar velocity field of the testing region. The third component of the velocity might have to be captured using specially designed stereoscopic equipment. When using the PIV method it is necessary to choose the seeding particle very carefully, following the main instructions of the manufacturer. The



Sl. 3. *Osnove merilne tehnike MHSSD [10] (korelacijska podobmočja in algoritem obdelave posnetkov)*
Fig. 3. *Basic principles of the PIV technique* [*10*] *(investigation areas and data processing)*

osemenjevalnih delcev ter njihova temperaturna občutljivost so bistvene značilnosti, ki narekujejo odmik dejanske od zaželene homogene porazdelitve delcev. Velikost in gostota sledilnih delcev, njihova odsevnost oz. razpršilni količnik, moč svetlobnega vira, trajanje laserskega sunka in časovni presledek med sunkoma ter morebitni paralaktični učinki so odločilnega pomena za uspešnost opravljenih meritev.

sedimentation and agglomeration properties of the seeding particles and their temperature sensitivity are the main features that have to be considered when we want to achieve a homogeneous distribution of added particles throughout the flow. Additional parameters concerning the seeding particles, which are important for successful data acquisition, are their size, density, and reflectivity, the power of the illumination system, the duration and delay of the laser pulses and the parallactic effects.

5 POTEK MERITEV

Meritve so potekale pri nasičenem vrenju vode in atmosferskem tlaku. Površine vrelne posode smo pred začetkom preizkusa vsakokrat očistili z razredčenim etanolom, posušili in izprali z destilirano vodo. Prehodni pojav, od zagona s sobne temperature do navidezustaljenih razmer v režimu mehurčastega vrenja, je trajal 30 min. Z namenom razplinjevanja vode v posodi, je ta pred začetkom meritev vrela najmanj 45 min.

Uporabili smo vrelne ploščice iz valjane jeklene zlitine W.Nr.1.4301 (DIN) z izmero 120×120×1 mm s svetlo poliranim sijajem površine (sl. 4a). Aritmetični srednji odstopek hrapavosti površine vrelne ploščice R_a je v smeri valjanja znašal 0,08 µm, v prečni smeri pa 0,1 µm. Umetno zarodno vdolbinico (sl. 4b) smo ustvarili z nadzorovanim prodorom stožčaste konice iz karbidne trdnine s 30° kotom izteka (sl. 4c). Povprečni premer zarodne votlinice je znašal 106 mm, ocenjena globina pa okrog 90 µm. Pred začetkom meritev smo v segreto vodo dodali približno 4 g/ℓ osemenjevalnih delcev najlona, povprečne velikosti 25 µm in specifične teže 1,03 kg/ℓ .

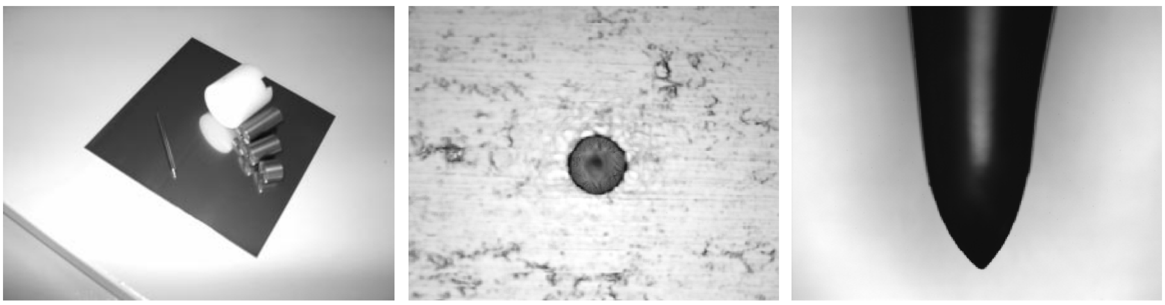
V primeru, da se je temperatura vode v posodi znižala pod 98 °C, je termostat ponovno vklopil sekundarni električni grelnik. Temperaturo vrelne ploščice smo ovrednotili posredno, preko temperature

5 MEASUREMENTS

All of the experimental results were achieved during the saturated boiling of distilled water at atmospheric pressure. Before the start of the experiment the internal surfaces of the boiling vessel were cleaned with diluted ethyl alcohol, dried and washed out in distilled water. The transition from cold state to the quasi-steady state condition in the nucleate boiling regime takes about 30 min., whereas the degasification of the water before the data acquisition lasts 45 min.

Fine polished boiling plates from rolled stainless-steel alloy W.Nr.1.4301 (DIN) with dimensions of 120×120×1 mm were used as the boiling surface (Fig. 4.a). The average roughness, R_a, in the rolling and lateral directions was 0.08 and 0.1 µm, respectively. A single micro-cavity (Fig. 4.b) on the boiling surface was produced by the mechanical impression of a needle nib, which was made from a hard metal. The conical peak of the impressing needle used here had a 30° angle at its tip (Fig. 4.c). The mean diameter of the produced cavities was 106 µm, whereas the estimated depth of the cavities was around 90 µm. The concentration of the added particles was approximately 4 g/ℓ. The seeding particles were made from nylon, with a mean diameter of 25 µm and a specific density of 1.03 kg/ℓ.

When the temperature of the water in the boiling vessel reaches 98°C, a secondary electrical heater is turned on by a thermostat immersed in the oil



(a) (b) (c)

Sl. 4. *Vtiskovanje zarodne vdolbinice: (a) fotografski posnetek vrelne ploščice s pripravo za vtiskovanje zarodne jamice (Fotona, d.d.), (b) mikroskopski posnetek zarodne jamice ob 20-kratni povečavi, (c) mikroskopski posnetek konice vtiskovalne igle ob 10-kratni povečavi (IJS - Reaktorski Center Brinje)*

Fig. 4. *Nucleation-site preparation: (a) photos of the boiling plate with micro-cavity immersion tools (Fotona, d.d.), (b) microscopic photos of artificially produced micro-cavity at a magnification of 20 times, (c) conical end of pitting needle at a magnification of 20 times (IJS - Reactor Center Brinje)*

olja na odtoku in dotoku v oljno kopel. Temperaturno znižanje oljnega toka je pri sedanji osamitvi sistema znašal manj ko 1 °C.

Izstopni optični modul laserja in vstopni filter objektiva kamere sta bila od vizualizacijskih odprtin vrelne posode oddaljena za 45 cm. Uporabili smo 1,3-kratno povečavo kamere, tako da smo iz dejanske velikosti opazovanega področja 76×61 mm dobili velikost posnetka 100×80 mm na 1280×1024 elementih zaslona kamere. Pri zbiranju podatkov je čas med dvema laserskima sunkoma znašal 1000 μs, svetlobna sunka sta trajala 0,01 μs, čas med zaporednima posnetkoma je bil 500 μs, velikost korelacijskega podobmočja pa je znašala 64×64 celičnih elementov.

6 REZULTATI MERITEV

Na slikah 5 do 8 so podani posnetki kamere in hitrostna polja opazovanega območja toka v štirih različnih časovnih trenutkih (t_0, t_1, t_2, in t_3) med izvajanjem meritev. Glede na vrisani koordinatni sistem so lege središč mehurjev podane s koordinatami: sl. 6 (v trenutku t_1) x = 43,2 mm, y = 5,9 mm; sl. 7 (v trenutku t_2) x = 41,5 mm, y = 16,1 mm; sl. 8 (v trenutku t_3) x = 41,5 mm, y = 37,6 mm. Na sliki 8 je vidno nastajanje novega mehurja nad zarodnim mestom. Tokovno polje okrog tega mehurja ni zajeto v tukaj podanem prikazu rezultatov.

Na slikah 9 do 11 so podani diagrami poteka navpične komponente hitrosti v režimu vrenja v časovnih trenutkih t_1, t_2, in t_3 (polne krivulje). Vsakokrat smo za prikaz izbrali tri vodoravne prereze vzdolž hitrostnega polja, ki ustrezajo neposredni bližini mehurja na posnetku

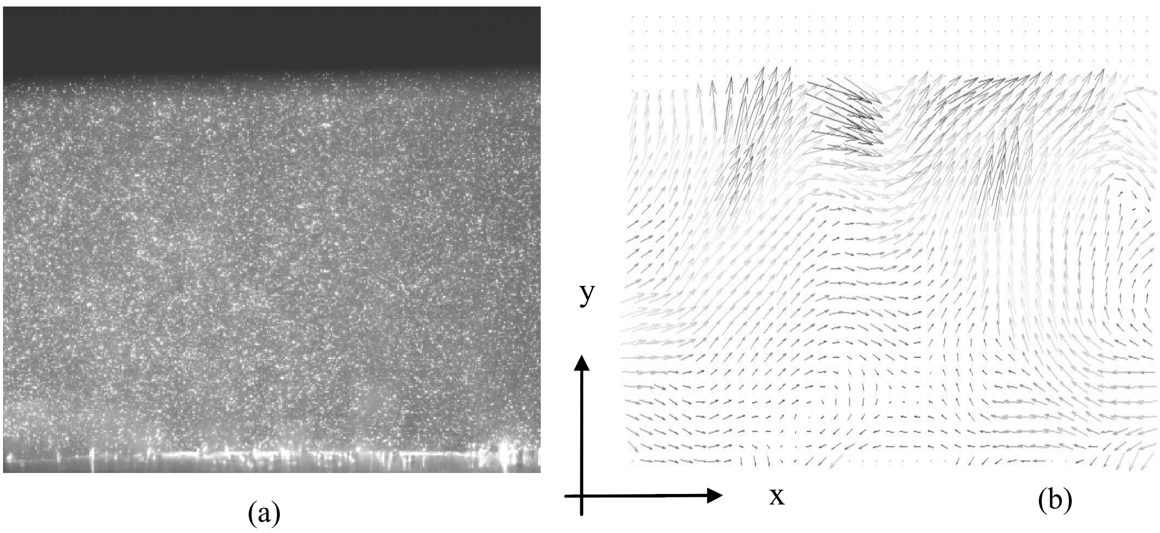
bath. The temperature of the boiling plate is estimated indirectly using the inlet and outlet temperatures of the oil bath. The temperature drop of the circulating oil was less then 1°C between these two points.

The light-sheet optics of the PIV laser and the green filter of the CCD camera objective are placed at a distance of 45 cm from the visualization openings of the boiling vessel. A magnification factor of 1.3 was used during the data acquisition. Thus, from 76×61 mm in physical space we obtained images with a size of 100×80 mm on the 1280×1024 elements of the light sensor. The time between two successive light pulses was 1000 μs, the duration of the light pulses was 0.01 μs and the time between successive images was 500 μs. A more suitable size of the investigated area wass selected, i.e., 64×64 pixels.

6 RESULTS

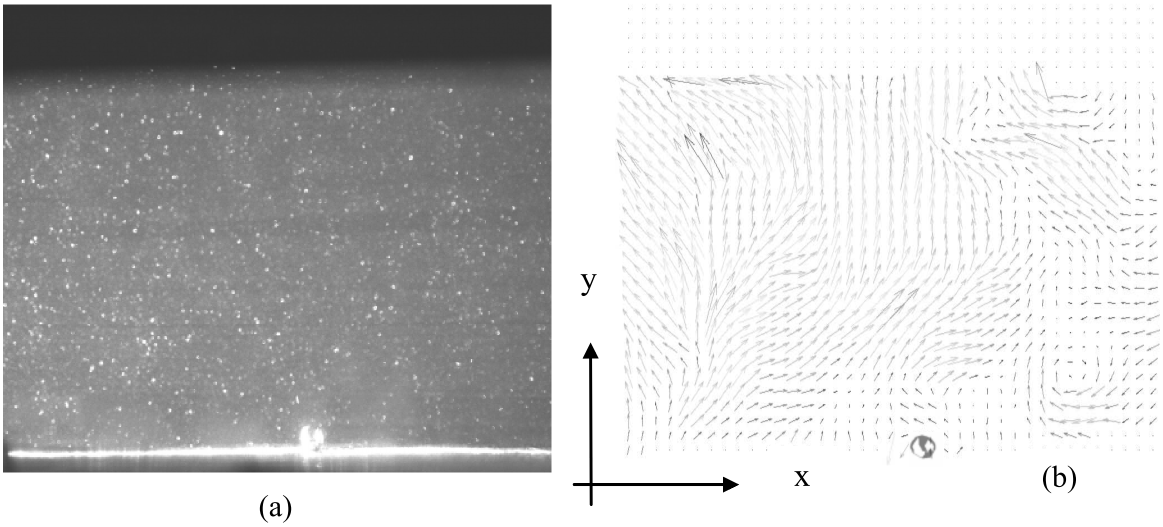
The PIV camera images and the resulting velocity fields for the selected visualization area are presented in Figures 5-8 for four different times (t_0, t_1, t_2, in t_3, respectively) during the experiment. For the drawn co-ordinate system the central positions of the vapour bubbles on these pictures are defined as follows: Fig. 6 (at time t_1) x = 43.2 mm, y = 5.9 mm; Fig. 7 (at time t_2) x = 41.5 mm, y = 16.1 mm; Fig. 8 (at time t_3) x = 41.5 mm, y = 37.6 mm. The formation of a new bubble over the nucleation site is also documented in Fig. 8. The velocity field around this bubble is not presented in the results analysed here.

The vertical velocity component profiles in the nucleate boiling regime at times t_1, t_2, in t_3 (full lines) are shown by the diagrams in Fig. 9-11. To produce these diagrams we used three horizontal sections along the velocity field, which are situated immediately in the vicinity of the vapour bubble position on the camera image. On each of the



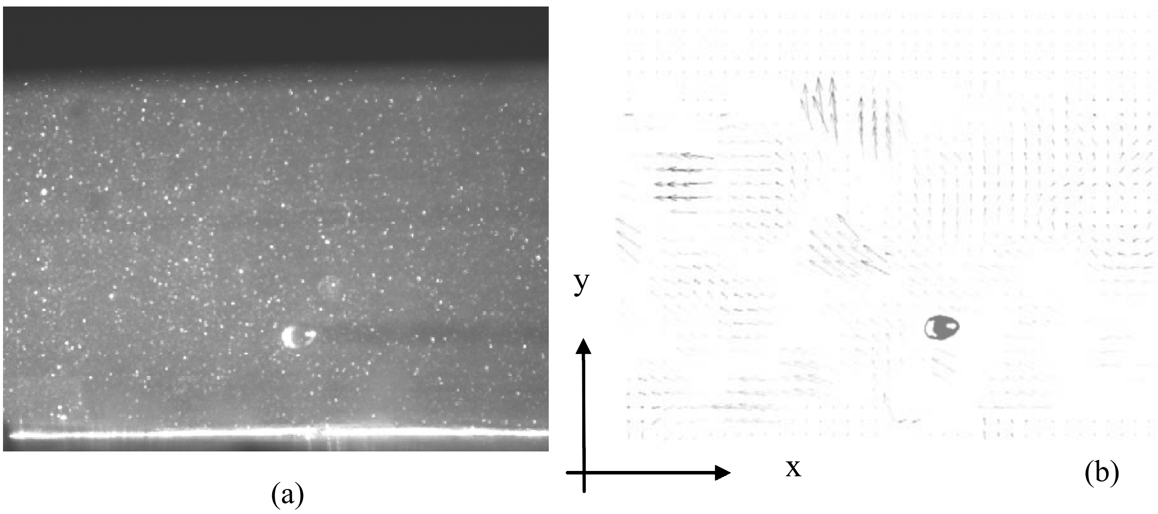
Sl. 5. *Odsevi sledilnih delcev na posnetku digitalne video kamere (a) in pripadajoče hitrostno polje (b) v trenutku t_0, med potekom naravne konvekcije pred začetkom mehurjenja nad zarodnim mestom*

Fig. 5. *Light reflection from seeding particles on the CCD camera image (a) and resulting velocity field (b) at time t_0 during the natural convection before the onset of boiling over the nucleation site.*



Sl. 6. *Odsevi sledilnih delcev na posnetku digitalne video kamere (a) in pripadajoče hitrostno polje (b) v trenutku* t_1*, med ločitvijo mehurja po začetku mehurjenja nad zarodnim mestom*

Fig. 6. *Light reflection from seeding particles on the CCD camera image (a) and resulting velocity field (b) at time* t_1 *during the bubble departure after the onset of boiling over the nucleation site.*

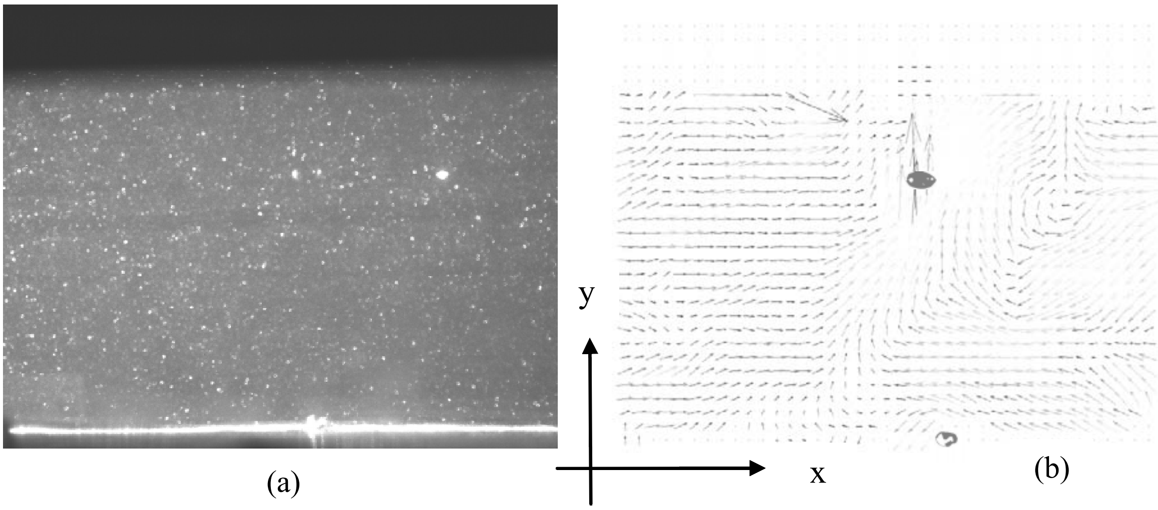


Sl. 7. *Odsevi sledilnih delcev na posnetku digitalne video kamere (a) in pripadajoče hitrostno polje (b) v trenutku* t_2*, med oddaljevanjem mehurja proti prosti gladini*

Fig. 7. *Light reflection from seeding particles on the CCD camera image (a) and resulting velocity field (b) at time* t_2 *during the bubble rising towards the free surface*.

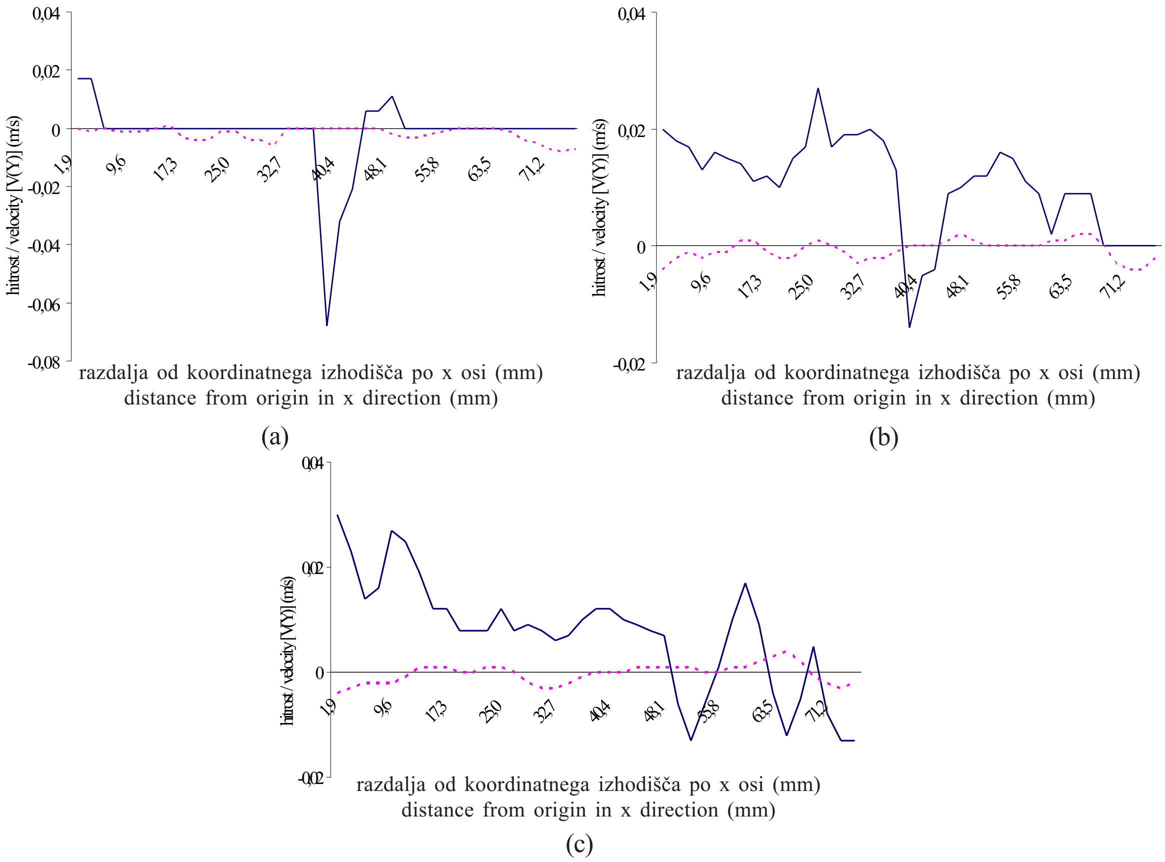
kamere. V vseh primerih prva izmed prerezov sekata tokovno brazdo oz. področje za mehurjem, medtem ko je tretji prerez pred mehurjem v smeri njegovega dviganja. Za primerjavo smo vsem diagramom dodali poteke navpične komponente hitrosti v polju naravne konvekcije (črtkane krivulje), ki smo jih izmerili v primerjalnem trenutku t_0 pred začetkom mehurjenja. Višinsko se prerezi za prikaz navpične komponente hitrosti v polju naravne konvekcije ujemajo s prerezi, ki so bili izbrani za prikaz navpične komponente hitrosti v režimu vrenja.

three presented sets of diagrams (a-c), the first two horizontal sections cross flow the field behind the bubbles, whereas the third one is placed immediately in front of the bubbles in the rising direction. Moreover, on each of the diagrams a vertical velocity component profiles in the natural convection, which were measured at time t_0 (dashed lines) before the onset of boiling are also added to simplify the comparison. The heights of the selected horizontal sections for the velocity profiles' presentation in the natural convection correspond to the heights of the sections chosen for the presentation of the velocity profiles extracted from the flow field during the nucleate boiling regime.



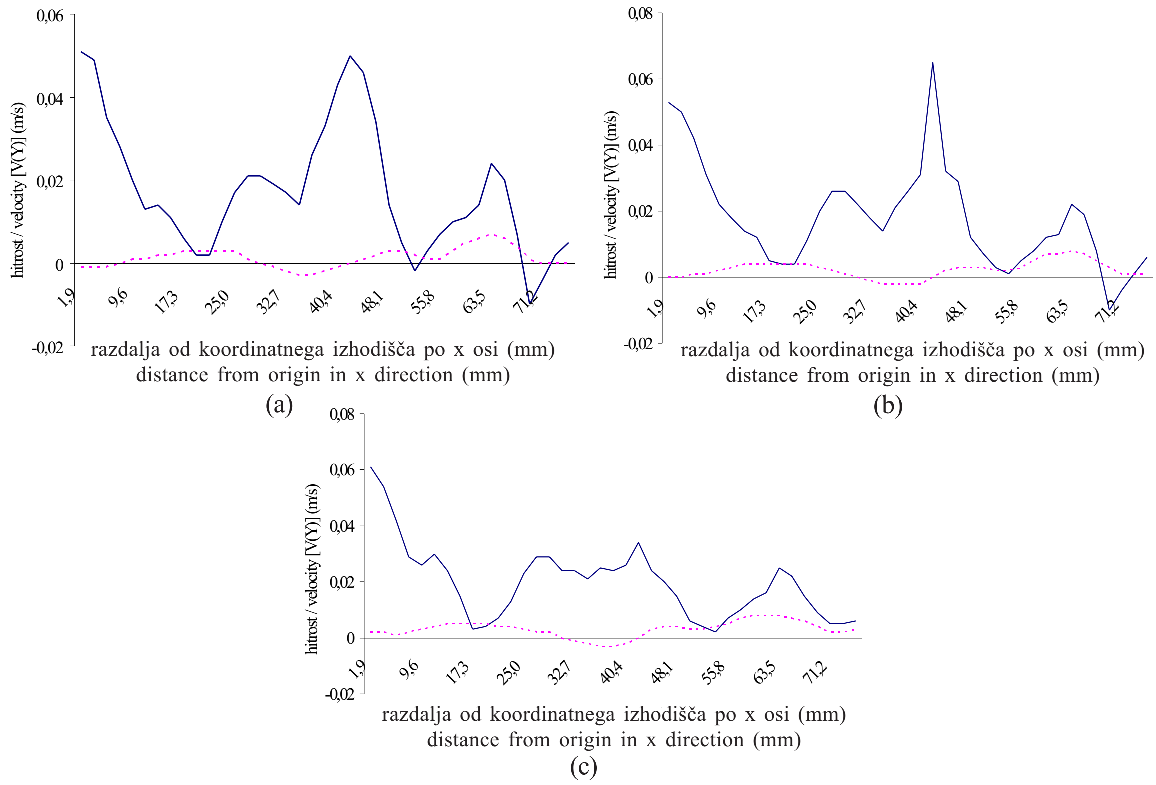
Sl. 8. *Odsevi sledilnih delcev na posnetku digitalne video kamere (a) in pripadajoče hitrostno polje (b) v trenutku t_3, med oddaljevanjem prvega in rastjo naslednjega mehurja nad zarodnim mestom*

Fig. 8. *Light reflection from seeding particles on the CCD camera image (a) and resulting velocity field (b) at time t_3 during the rising of the first bubble and growth of another one over the nucleation site.*



Sl. 9 (a do c). *Diagrami navpične komponente hitrosti V_y med potekom vrenja v trenutku t_1 (sl. 6)(polne krivulje) in pred začetkom vrenja v trenutku t_0 (sl. 5)(črtkane krivulje) v izbranih vodoravnih prerezih merilnega polja. Višina prereza na sl. 9(a): y = 1,9 mm (področje za mehurjem); višina prereza na sliki 9(b): y = 3,8 mm (področje za mehurjem); višina prereza na sliki 9(c): y = 5,8 mm (področje pred mehurjem).*

Fig. 9 (a to c). *Diagram of vertical velocity components V_y during the bubble boiling at time t_1 (Fig. 6)(full line) and before the onset of boiling at time t_0 (sl. 5)(dashed line) along the selected horizontal sections of flow field. Height of reference plane on Fig. 9(a): y = 1.9 mm (region behind the bubble); height of reference plane on Fig. 9(b): y = 3.8 mm (region behind the bubble); height of reference plane on Fig. 9(c): y = 5.8 mm (region in front of bubble).*



Sl. 10 (a do c). *Diagrami navpične komponente hitrosti* V_y *med potekom vrenja v trenutku* t_2 *(sl. 7)(polne krivulje) in pred začetkom vrenja v trenutku* t_0 *(sl. 5)(črtkane krivulje) v izbranih vodoravnih prerezih merilnega polja. Višina prereza na sl. 10(a): y = 13,5 mm (področje za mehurjem); višina prereza na sliki 10(b): y = 15,4 mm (področje za mehurjem); višina prereza na sliki 10(c): y = 17,3 mm (področje pred mehurjem).*

Fig. 10 (a to c). *Diagram of vertical velocity components* V_y *during the bubble boiling at time* t_2 *(Fig. 7)(full line) and before the onset of boiling at time* t_0 *(Fig. 5)(dashed line) along the selected horizontal sections of flow field. Height of reference plane on Fig. 10(a): y = 13.5 mm (region behind the bubble); height of reference plane on Fig. 10(b): y = 15.4 mm (region behind the bubble); height of reference plane on Fig. 10(c): y = 17.3 mm (region in front of bubble).*

Potek hitrosti v režimu mehurčastega vrenja na diagramih (a) in (b) na sliki 9 nazorno prikazuje zalitje vrelne površine med ločevanjem mehurčka. Sesalni učinek in intenzivnost gibanja v tokovni brazdi za dvigajočim se mehurjem sta razvidna iz diagramov (a) in (b) na slikah 10 in 11. Izrazit hitrostni vrh v navpični smeri na diagramu (c) na sliki 11 je posledica pojemajoče tokovne brazde predhodnega mehurja. Primerjava navpičnih komponent vektorjev hitrosti kaže, da je intenzivnost gibanja kapljevine v navpični smeri v režimu vrenja za en velikostni razred večja od intenzivnost gibanja v isti smeri med potekom naravne konvekcije pred pričetkom mehurjenja.

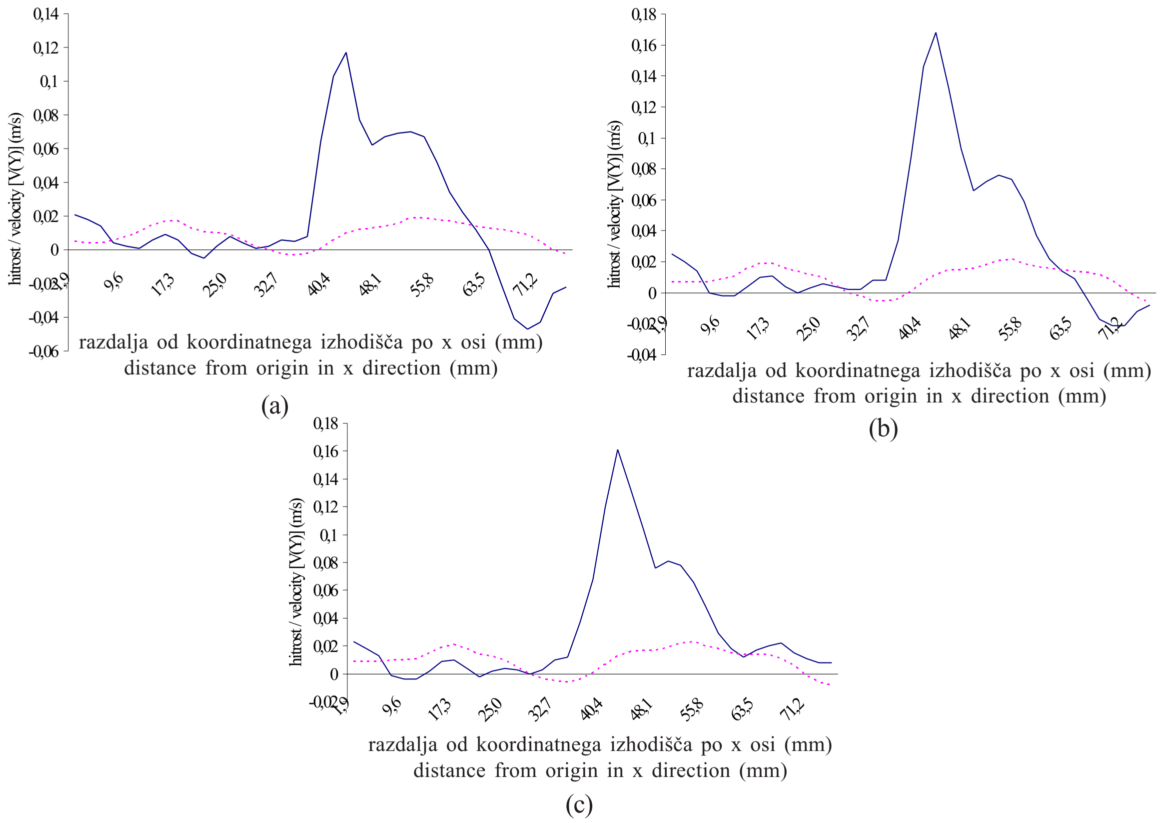
From the vertical velocity component profiles shown by diagrams (a) and (b) in Figure 9 it is evident that an intensive immersion of the boiling surface occurs during the bubble departure over the nucleation site. The suction effect and the large velocity gradients in the flow wake behind the bubble are shown by diagrams (a) and (b) in Figures 10 and 11. The high-velocity peak in the vertical direction on the diagram (c) in Figure 11 appears as a result of the flow wake formed behind a previously released bubble. An analysis of the velocity distribution showed that the vertical velocity components during the bubbling process are one order of magnitude higher than in the regime of natural convection before the onset of boiling.

7 SKLEPI

Večina do sedaj opravljenih raziskav mehurčastega vrenja temelji na preučevanju temperaturnega polja vzdolž vrelne površine. Meritve hitrostnega polja so redke. Visoka frekvenca tvorbe parnih mehurjev, majhna razsežnostna skala pojava, veliko število zarodnih mest ter pomanjkljivosti preizkusnih metod vrednotenja

7 CONCLUSION

A large number of the investigations of nucleate boiling were conducted using experimental data of the temperature field along and over the boiling surface. Velocity-field measurements are almost unknown. The high released frequency of the vapour bubbles, the low dimensional scale of the phenomenon, the large number of nucleation sites and the crucial restrictions of the



Sl. 11(a do c). *Diagrami navpične komponente hitrosti V_y med potekom vrenja v trenutku t_3 (sl. 8)(polne krivulje) in pred začetkom vrenja v trenutku t_0 (sl. 5)(črtkane krivulje) v izbranih vodoravnih prerezih merilnega polja. Višina prereza na sl. 11(a): y = 34,6 mm (področje za mehurjem); višina prereza na sliki 11(b): y = 36,5 mm (področje za mehurjem); višina prereza na sliki 11(c): y = 38,5 mm (področje pred mehurjem).*

Fig. 11 (a to c). *Diagram of vertical velocity components V_y during the bubble boiling at time t_3 (Fig. 8)(full line) and before the onset of boiling at time t_0 (Fig. 5)(dashed line) along the selected horizontal sections of flow field. Height of reference plane on Fig. 11(a): y = 34.6 mm (region behind the bubble); height of reference plane on Fig. 11(b): y = 36.5 mm (region behind the bubble); height of reference plane on Fig. 11(c): y = 38.5 mm (region in front of bubble).*

hitrostnega polja v režimu vrenja so bile v preteklosti težko premostljiva ovira. Z razvojem laserskih merilnih tehnik MHSSD in LDA so se tudi na tem področju odprle nove možnosti.

Kolikostno vrednotenje izsledkov preizkusnih raziskav hitrostnega polja, kjer bi bile zajete zapletene interakcije številnih zarodnih mest, njihova sprožitev in deaktivacija ter vpliv le-teh na prenos toplote z grelnika na tekočino, predstavlja zahteven fizikalno-matematični model. Tukaj smo ubrali bolj preprosto pot. Omejili smo se na analizo lokalnih tokovnih razmer v okolici osamljenega mehurčka, kar omogoča vpogled v temeljne fizikalne zakonitosti pojava. Doseženi rezultati potrjujejo pomen mikrokonvektivnih tokov kot enega izmed pomembnih mehanizmov prenosa med potekom vrenja. Določene izboljšave eksperimentalne naprave, vizualizacija in meritve tokovnega polja v neposredni okolici mehurja, združitev metode MHSSD s tehniko HDVK ter samodejna sinhronizacija merilne opreme z nastajanjem mehurjev na vrelni ploščici so naslednji koraki, ki bodo opravljeni v nadaljevanju raziskave.

experimental techniques affected the successful imaging of the flow field in bubble boiling. Non-invasive PIV and LDA techniques give us some new possibilities to research the hydrodynamics of the boiling process.

An investigation of the flow-field distribution, where it is needed to capture the mutual interactions between numerous nucleation sites, their activation and deactivation mechanisms and the impact of this process on the heat transfer, can be found as a very complex physical model. To avoid these difficulties we analysed the nucleation process only at one artificially produced nucleation site. A flow-field analysis in the vicinity of a single bubble allows us to obtain some insight into the fundamental features of the bubbling process. The results confirm micro-convection as one of the important transport mechanisms during nucleate boiling. Some improvements to the boiling apparatus, the visualization and the measurements of the velocity field immediately in the vicinity of vapour bubble interface, the combination of PIV and DHSVC techniques and the synchronisation of the data-acquisition process with bubble production on the boiling surface will be done in the future.

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