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Intelligent thermal management for full electric vehicles *

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Abstract: Thermal management plays a crucial role in the development of efficient electric vehicles. Namely, in the case of energy demands during power peaks, major losses occur in power electronic devices during the vehicle's driving cycle. The flexibility required to efficiently dissipate the energy released in power electronic devices suggests the development of innovative intelligent thermal management systems, able to respond to these power peaks. In this paper, the spray cooling technology is explored toward an intelligent thermal management, using intermittent sprays produced by multijet impingement atomization. The heat losses consider the typical values found in IGBT semiconductor devices, such as converters, or inverters. The analysis is based on the correlation between the spray characteristics and the surface thermal behaviour, from the point of view of an active control of the cooling process, as well as the quantification of the benefit from phase-change.

*** Napredno upravljanje toplinom kod potpuno električnih vozila**

Izvorni znanstveni rad

Sažetak: Upravljanje toplinom igra ključnu ulogu u razvoju efikasnih električnih vozila. Naime, u slučaju potrošnje električne energije za vrijeme vršnih opterećenja, najveći gubici snage električnih uređaja javljaju se za vrijeme ciklusa vožnje. Potrebna fleksibilnost za učinkovitu potrošnju električne energije koja se troši u električnim uređajima sugerira razvoj inovativnih sustava za napredno upravljanje toplinom, koji će moći zadovoljiti vršna opterećenja. U ovom radu ispitivala se tehnologija hlađenja sprejem usmjerena k naprednom upravljanju toplinom, koristeći isprekidana raspršivanja koji se proizvode automatiziranim višemlaznim sudaranjem. Za gubitke topline uzimaju se u obzir tipične vrijednosti koje se nalaze u poluvodičkim IGBT uređajima, kao što su pretvarači ili izmjenjivači. Analiza se temelji na vezi između karakteristika raspršivača i temperaturnog odziva površine s gledišta aktivne kontrole rashladnog procesa, kao i kvantifikacije koristi od promjene faze.

1. Introduction

The development of Full Electric Vehicles (FEV) as sustainable transports capable of withstanding harsh environments and different driving user needs strongly depends on the efficient use of energy driving electrical machines by power electronic devices (e.g. inverters), as well as subsystems for power conversion (e.g. Direct-Current/Direct-Current converters). In order to ensure the competitiveness of electric vehicles through such an efficiency increase, power density should increase along with the development of smaller, lighter and, consequently, cheaper power electronic components, namely, IGBT based power modules. However, such a trend faces the increasing challenges of thermal management. For example, the switching losses of an IGBT power module may represent about 50% of total power losses [1], but an increase of power density supplied to the electric motor implies an increase in switching frequencies [2], therefore, devising an appropriate thermal control is crucial to enable an advanced performance of FEVs by overcoming heat losses in power electronics and electrical machines (PEEM) [3].

In order to overcome the current limitations imposed by these thermal losses on semiconductor devices (IGBT modules), for conditions typically found in full electric vehicles, the most promising cooling technologies rely on two-phase flows, taking advantage of the latent heat of evaporation. However, it is unclear how can we quantify the benefit from phase-change, particularly in the spray cooling technique explored in this work. Moreover, the spray cooling performance depends on the kind of atomization that produces the spray, its characterization in terms of size and velocity of droplets, operation mode, and the interaction between the impinging spray and the heated surface.

Symbols/Oznake

c_p	-	coolant specific heat / specifična rashladna toplina, J kg^{-1}K^{-1}
Ca_d	-	droplet Capillary number / kapilarni broj kapljica
d_{10}	-	droplet mean diameter / prosječni promjer kapljice, μm
d_j	-	jet diameter / promjer mlaza, μm
DC	-	injection duty cycle / radni ciklus ubrizgavanja, %
f_{inj}	-	injection frequency / frekvencija ubrizgavanja, Hz
$f_{mix,K}$	-	pdf's finite mixture / pdf konačna smjesa
F_{mix}, F_i	-	cumulative pdf / kumulativni pdf
FEV	-	Full Electric Vehicle / Potpuno električno vozilo
g	-	generic function / opća funkcija
h_{fg}	-	latent heat of vaporization / latentna toplina isparavanja, J kg^{-1}
h_{sc}	-	spray cooling heat transfer coefficient / koeficijen prijelaza topline kod hlađenja raspršivanjem, W m^{-2}K^{-1}
IGBT	-	Insulated Gate Bipolar Transistor / Izolirani izlaz bipolarnog tranzistora
Ja	-	Jakob number / Jakob-ov broj
K	-	number of pdf's used in the finite mixture / broj pdf koji se koristi u konačnoj smjesi
k_f	-	coolant thermal conductivity / toplinska provodnost rashlađivača, Wm^{-1}K^{-1}
La_d	-	droplet Laplace number / Laplaceov broj kapljice
$\dot{m}''_f$	-	mass flux / maseni protok, kg s^{-1}
$\dot{m}''_{LF}$	-	accumulated liquid film mass flux / akumulirani tekući sloj masenog toka, kg s^{-1}
ML	-	Marginal Likelihood / Granična vjerojatnost
N_j	-	number of impinging jets / broj pridodanih mlaznica
w	-	weight of a pdf / težina pdf-a
We	-	Weber number / Weberov broj
x	-	generic variable / opća varijabla

Greek letters/Grčka slova

A	-	degree of liquid deposition / razina tekućeg taloga
B	-	generic characteristic parameters / opći karakteristični parametri
ΔT_{bf}	-	subcooling degree / stupanj pothlađivanja, K
Δt_{inj}	-	injection duration / vrijeme ubrizgavanja, ms
$\overline{\Delta t_{inj}}$	-	non-injection duration / vrijeme bez ubrizgavanja, ms
γ	-	surface tension / napetost površine, N m^{-1}
η	-	spray cooling efficiency / učinkovitost hlađenja raspršivanjem, %
θ	-	jet half-impingement angle / kut mlaza na pola pada, º
μ_f	-	fluid dynamic viscosity / dinamička viskoznost fluida, Pa s
μ_i	-	characteristic mean parameter / karakteristični srednji parametar
ρ	-	density / gustoća, kg m^{-3}
σ	-	characteristic standard deviation / karakteristično standardno odstupanje
χ	-	benefit of phase-change parameter / korist promjene faze parametara

Nu	-	Nusselt number / Nusseltov broj			**Subscripts/Indeksi**
PEEM	-	Power Electronic and Electrical Machines / Energetska elektronika i električni uređaji	$_c$	-	critical / kritično
pdf	-	probability density function / funkcija gustoće vjerojatnosti	$_d$	-	droplet / kapljice
$\dot{q}''_{diss}$	-	dissipated heat / rasipanje topline, W m^{-2}	D	-	diameter / promjer
$\dot{q}''_{sens}$	-	sensible heat / osjetna toplina, W m^{-2}	$_{inj}$	-	injected / ubrizgavanje
$\dot{V}''_{inj}$	-	injection cycle volume flow rate / ciklus ubrizgavanja volumena protoka, m^{3}s^{-1}	$_j$	-	jet / mlaz
T_b	-	boiling temperature / temperatura vrenja, K	U	-	axial velocity / aksijalna brzina
T_f	-	coolant temperature / temperatura rashladne tvari, K			
TTL	-	Transistor-Transistor Logic / Tranzistor-tranzistor logika			
U_j	-	jet velocity / brzina mlaza, m s^{-1}			

Through the advanced statistical tool of the finite mixture of probability density functions (pdf), drop size and axial velocity distributions are involved in the physical interpretation of the flow, instead of limiting it to first and second order distribution moments. Each group of droplets with similar size characteristics has been modelled by lognormal distributions, and normal distributions relative to drop axial velocity. Furthermore, droplet characteristics are correlated with the heat transfer rate for several operating conditions that maintain the surface temperature in the steady-state at 125ºC, which is the operating value recommended for IGBT-based power electronic devices. The effect of the time between consecutive injections is analysed.

Relative to the spray operating mode, most research works reported do not take into account an active control of the cooling process required for an intelligent thermal management during periods of transient heat loads. The active control of heat transfer can be interpreted as a spatial control [4], or temporal control over the flow rate using an intermittent spray [5, 6]. Considering the point of view of developing two-phase cooling technologies that take benefit from phase-change, intermittent spray cooling is compared with the current proposals based on continuous sprays. While the correlation between droplets characteristics and heat transfer only consider the spray produced by the impact of 3 jets, when comparing the benefit from phase-change, the sprays produced by the impact of 2 and 4 jets are also taken into account. The synthesis of the scattered information on this subject provides the guidelines for research trends in the development of intelligent thermal management technology.

2. Methodology

2.1. Experimental setup

The characterized spray issues from a multijet impingement atomizer with N_j = 3 impinging jets making an impact angle (2θ) between them of 90° and equally spaced in terms of azimuthal angle. The jets are considered to have the same diameter d_j = 400 μm as the hole in the atomizer. The liquid supply line works in a closed circuit and a pressure regulation valve allows controlling its value in the monorail coupled with the injector. This pressure has been set to the same value used in the heat transfer experiments previously reported [7], corresponding to 1.6 bar. For this pressure differential at the atomizer exit, a nominal volumetric flow rate of 3.33 ml/s is obtained with the injector valve fully open, and it varies depending on the duty cycle ($\mathrm{DC} \in [0\%, 100\%]$, see Fig. 1) as $\dot{V}''_{inj}(\mathrm{DC}) = \mathrm{DC} \cdot \dot{V}''_{inj}(100\%)$. Each jet velocity is 8.8m/s. The liquid is methanol, which is a dielectric fluid with a density (ρ) of 781.6 kg/m^3, dynamic viscosity (μ) of 5.249×10^{-4} kg/(m/s), surface tension (γ) of 21.92 mN/m at 30°C, thermal conductivity (k_f) of 0.2033 W/m/K and a latent heat of vaporization (h_{fg}) of 1168 kJ/kg.

Heat transfer experiments previously reported considered the effect of the non-injection time between consecutive injections $(\overline{\Delta t_{inj}})$ as it is illustrated in Fig. 1 [7]. These non-injection times have been set to 10, 20 and 40 ms while keeping a constant duty cycle (DC, see definition in Fig. 1, where f_{inj} is the injection frequency and Δt_{inj} the duration of injection). Thus, a decrease of this period means that the amount of mass injected in the largest cycle $(\overline{\Delta t_{inj}} = 40\mathrm{ms})$ is actually being distributed into multiple injections (see illustration in the lower-left part of Fig. 1).

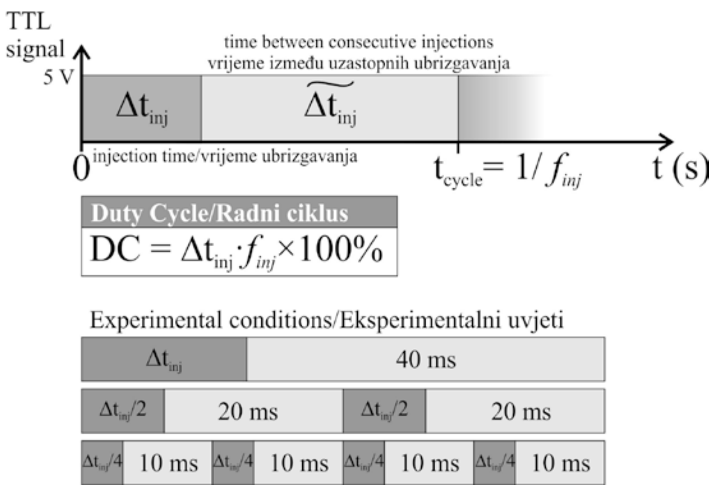
The heat transfer results reported in Panão *et al.* [7] will be used in this work in order to correlate with the spray droplet's characteristics. These (size and axial velocity of droplets) have been measured with a Phase-Doppler Interferometer collecting the light dispersed by droplets at a scattering angle of 74°, which corresponds to the Brewster angle for methanol, with the purpose of minimizing the reflected light with a parallel polarization. The beam spacing is 60 mm and both transmitting and receiving lens have a 500 mm focal length, thus, the maximum measurable diameter is 350 μm.

2.2. Statistical method for spray characterization

The data on the size and axial velocity of droplets in this work is statistically described by discrete probability density distributions. Usually, these distributions are further used in a statistical analysis, which is based on its moments, *e.g.* mean quantities or standard deviation. However, it has been argued in a previous work that such approach, although correct, gives only a partial and limited knowledge of the measured distribution [8]. On the other hand, for the development of numerical models, it is an advantage to describe such distributions by mathematical pdf functions (e.g. Lognormal) or empirical models (*e.g.* Nukyiama-Tanasawa, Rosin-Ramler, Weibull, for a comprehensive review see Babinsky and Sojka [9]). However, probability distributions describing sprays are often multimodal, or presented with heterogeneities. Thus, when the actual distribution is approximated to a unimodal mathematical function, with its characteristic parameters, and the latter are used to evaluate geometric, operating or environmental parametric effects on the spray formation and development, the analysis becomes limited. In order to overcome these limitations, in this work, discrete probability distributions characterizing the spray have been mathematically modelled using the known statistical tool of finite mixtures of probability density functions. This tool consists in identifying the number K of groups of droplets with similar characteristics and empirically fitting the discrete probability distribution to a linear combination of weighted probability density functions as

$$f_{mix,K}(x) = \sum_{i=1}^{K} w_i f(x|\beta_i) \qquad (1)$$

where w_i is the weight and β_i are the characteristic parameters of the mathematical probability density function. In the experimental characterization reported here, for each group of droplets, the size has been modelled by a Lognormal pdf $\left(\vec{\beta_D} = \{\mu_{i,D}, \sigma_{i,D}\}\right)$, and drop axial velocity by a Normal pdf $\left(\vec{\beta_U} = \{\mu_{i,U}, \sigma_{i,U}\}\right)$. The fitting procedure followed a Bayesian approach previously applied to sprays by Panão *et al.* [8] and Panão and Radu [10]. Therefore, instead of using characteristic means values, which are limited for describing multimodal drop size and velocity distributions, the parameters of the finite mixture are used instead. The same formulation for a finite mixture given in eq. (1) can also be used with cumulative distribution functions (F_{mix} or F_i). In terms of flow analysis, this ultimately means that the entire distribution is being considered, and not just its moments. The best finite mixture is that which maximizes the Marginal Likelihood (ML) or the minimum K above which ML stabilizes [10]. The resulting finite mixtures obtained have been subjected to a chi-squared test with a 99.9% of confidence interval and the hypothesis that the mathematical curve fits data has been accepted in all cases.



DC (%)	f_{inj} (Hz)	$\widetilde{\Delta t_{inj}}$ (ms)
40	60	10
	30	20
	15	40
55	45	10
	22.5	20
	11.25	40
70	30	10
	15	20
	7.5	40
85	15	10
	7.5	20
	3.75	40
100	0.01	0

Figure 1. Illustration of the spray injection cycle and description of the experimental conditions considered for studying the effect of the spray intermittency on heat transfer.

Slika 1. Prikaz ciklusa ubrizgavanja raspršivanjem i opis eksperimentalnih uvjeta koji su uzeti u obzir u proučavanju učinka isprekidanog raspršivanja na prijelaz topline.

2.3. Quantifying the benefit from phase-change

The main advantage of a two-phase cooling is to benefit from phase-change. If we assume a subcooling $\Delta T_{bf} = T_b - T_f$ other than zero, when the spray impacts onto the heated surface, part (and ideally all) of the injected liquid deposits on the surface and its temperature increases up to the liquid's boiling point at ambient isobaric conditions, through the removal of sensible heat $\dot{q}''_{sens} = \dot{m}''_f c_p \Delta T_{bf}$ from the surface. Afterwards, a large portion of heat is removed by phase-change through evaporation by mass diffusion at the liquid-vapour interface in a non-saturated environment and non-boiling regime; or else, in a nucleate boiling regime, with the formation of bubbles at the solid-liquid interface. Thus, heat transfer performance depends on liquid film formation and dynamics, as well as the complex flow generated by nucleate boiling. Additionally, the hydrodynamics associated with multiple drop impacts [11], or the formation of secondary nuclei through vapour entrainment from the liquid-vapour interface [12], have their important role in heat transfer processes. Namely, Zhao *et al.* [13] have validated a model which allows for the assessment of the relative importance on heat transfer between: *i*) drop-wall impaction; *ii*) film-wall convection; *iii*) heat dissipated to the environment; *iv*) and bubble boiling; concluding that for the range of heat fluxes expected to dissipate in IGBT's (200-300 W/cm^2), the main influences are due to drop impaction and bubble boiling, expressing a strong relation between both hydrodynamic mechanisms and phase-change. However, the research question is how to quantify how much benefit or not does a system take from phase-change.

Given the above description, in order to quantify the benefit associated with phase-change, we first consider that the heat dissipated by the spray ($\dot{q}^*_{diss}$) is removed by the part of liquid which accumulates on the surface in the form of a liquid film $\dot{m}''_{LF} = \alpha \dot{m}''_f$, where α is null for no deposition, or 1 for a full deposition. Also, thermodynamically, unless the subcooling degree ΔT_{bf} is zero, the accumulated liquid film exchanges sensible heat to increase its temperature up to the boiling value for local ambient conditions, while the remaining heat is exchanged through a non-boiling, or boiling phase-change. This can be expressed as

$$\dot{q}''_{diss} = \alpha \rho \dot{V}''_{inj} \left(c_p \Delta T_{bf} + \chi h_{fg} \right) \quad (2)$$

where $\dot{V}''_{inj}$ is the volumetric flow rate injected, ρ, c_p and h_{fg} are the liquid's density, specific heat and latent heat of vaporization, respectively. Parameter χ is our proposal for quantifying the "*benefit from phase-change*" between different spray cooling systems. Using this parameter for comparison purposes implies taking into account not only different cooling liquids, but also different relations between heat transfer and spray impact hydrodynamics.

In order to explain this, eq. (2) is solved for χ, becoming a function of two terms: *i)* a normalized heat flux $\dot{q}^*_{diss} = \dot{q}''_{diss} / \left(\alpha \rho \dot{V}''_{inj} h_{fg} \right)$; *ii)* and the Jakob number Ja $= c_p \Delta T_{bf} / h_{fg}$ as

$$\chi = \dot{q}^*_{diss} - \text{Ja} \quad . \quad (3)$$

Relative to the Jakob number (Ja), a liquid with a smaller Ja is more likely to benefit from phase-change, than one with a higher Ja, although one can always reduce Ja by decreasing the subcooling degree. The normalized heat flux term $\dot{q}^*_{diss}$ stands for implications of the relation between heat transfer and the liquid accumulated on the surface for cooling purposes, relative to the benefit from the phase-change a thermal management system might retrieve. It can be easily understood that: if $\chi = 0$ there is no benefit from phase-change; while $\chi = 1$ implies full benefit. Moreover, in order to understand the theoretical limits of χ, we consider the general definition of cooling efficiency η

$$\eta = \frac{\dot{q}''_{diss}}{\rho \dot{V}''_{inj} \left(c_p \Delta T_{bf} + h_{fg} \right)} \quad (4)$$

which could be included in Eq. (3) resulting in

$$\chi = \frac{\eta}{\alpha} + Ja \left(\frac{\eta}{\alpha} - 1 \right) \quad . \quad (5)$$

If one considers the several physical constraints associated with the parameters involved, relative to the most unknown variable, which is the fraction of liquid injected that accumulates on the surface α, $\{0 \le \chi, \eta, \alpha \le 1; \text{Ja} \ge 0;\}$, it yields as a solution the following cases:

1. if $\eta = 0$ and Ja = 0, the partial deposition of liquid α may assume any of its values within its physical limits;
2. if $\eta = 1$ and Ja ≥ 0, full deposition is expected with $\alpha = 1$;
3. if Ja is compared with the ratio $\eta^* = \eta/(1-\eta)$, the partial deposition of liquid α is expected to lie between the value of the cooling efficiency η and a maximum of 1 if Ja $\le \eta^*$, or $\eta(1+\text{Ja})/\eta$ if Ja $> \eta^*$.

In the first case, when η tends to 0%, and Ja is very small, the latent heat may be high relative to the sensible heat, but there is little or no benefit from phase-change $(\chi \to 0)$, corresponding to a spray impact on a non-heated surface. In the second case, obviously, an efficiency of 100% could only mean total deposition of the liquid injected and full benefit from phase-change $(\chi = 1)$. The third case sets a physical minimum of accumulated liquid (η), and a physical maximum depending on the relation between Ja and the coefficient η*. Moreover, if the minimum physical amount of liquid is accumulated (α = η), a total benefit from phase-change is expected (χ = 1); or else if the maximum is accumulated, phase-change is fully mitigated (χ = 0).

3. Results and discussion

3.1. Spray characteristics

The set of results presented corresponds to a multijet impingement atomizer with three impinging jets ($N_j = 3$). Firstly, one considers the characteristic parameters (w_i, μ_i, σ_i) of the finite mixture that best describes the distribution of drop sizes for the experimental conditions included in the table of Fig. 1. In all the spray intermittency conditions, the best finite mixture describing the discrete probability distribution is made of three groups of droplets (K = 3). An example of the discrete and its finite mixture of cumulative drop size distributions is given in Fig. 2.

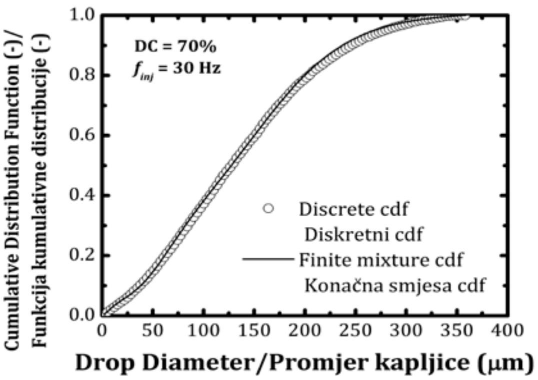


Figure 2. Example of the discrete cumulative size distribution and the corresponding finite mixture of K = 3

Slika 2. Primjer diskretne kumulativne raspodjele veličine i odgovarajuće konačne smjese za K=3

In Fig. 3, the characteristic mean diameter $\mu_{i,D}$ of every group of droplets identified is plotted against the standard deviation $\sigma_{i,D}$, and the size of symbols is proportional to the weight w_i that each cluster described by $f_i(x|\mu_{i,D}, \sigma_{i,D})$ has within the finite mixture $f_{mix,K}(x)$. Therefore, the first group with a lognormal distribution centered on small droplets, widely polydispersed, is the least representative, while the remaining two clusters have similar weights. There are two noteworthy observations in these results. The first is the fact that $\mu_{i,D}$ is well correlated with $\sigma_{i,D} = g(\mu_{i,D})$, representing a simplification when describing the spray characteristics by reducing the need of two parameters to one, $f_i(x|\mu_{i,D}, g(\mu_{i,D}))$. The second observation is that changing the spray intermittency does not seem to significantly affect the correlation between $\mu_{i,D}$ and $\sigma_{i,D}$ for the experimental conditions considered.

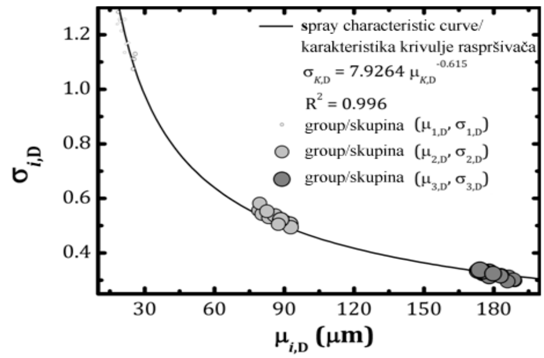


Figure 3. Correlation between the characteristic mean diameter $\mu_{i,D}$ and the standard deviation $\sigma_{i,D}$

Slika 3. Veza između karakterističnog srednjeg promjera $\mu_{i,D}$ i standardne devijacije $\sigma_{i,D}$

Relatively to spray impaction, the most important velocity component is the axial one, perpendicular to the wall (U). Thus, our analysis also includes discrete probability distributions of droplets axial velocity. In this case, Normal distributions describe the experimentally obtained discrete pdf with reasonable accuracy and the best mixture is obtained for K = 2, therefore, two clusters were identified (Fig. 4). However, the cluster with the lowest characteristic velocity values and higher RMS has a negligible overall weight. Therefore, the main focus is given to the second cluster ($\mu_{2,U}$, $\sigma_{2,U}$).

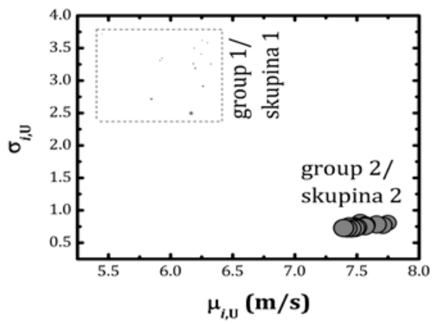


Figure 4. Correlation between the characteristic mean diameter $\mu_{i,U}$ and the standard deviation $\sigma_{i,U}$ of drop axial velocity

Slika 4. Veza između karakterističnog srednjeg promjera $\mu_{i,U}$ i standardne devijacije $\sigma_{i,U}$ aksijalne brzine kapljice

The standard deviation $\sigma_{2,U}$ varies only 1.8% between cases, and the variability of $\mu_{2,U}$ is also moderate, about 6.2%. In fact, the maximum variation between operating conditions is approximately 47% of average standard deviation of all operating conditions, indicating that the effect of the spray intermittency of the spray characteristics is relatively low. Nonetheless, if this component is correlated with the duty cycle (DC), one observes a systematic pattern where the axial velocity distribution shifts to lower characteristic values for every non-injection time condition (see Fig. 5). Namely, for lower DC's, the effect of injection splitting is slightly more pronounced.

Relative to droplet size, given the presence of three groups of droplets, a weighted characteristic mean diameter is considered and defined as $\mu_{K,D} = \sum_{i=1}^{K} w_i \mu_{i,D}$, and when plotted against DC, unlike droplets axial velocity, the absence of correlation becomes evident (see Fig. 6).

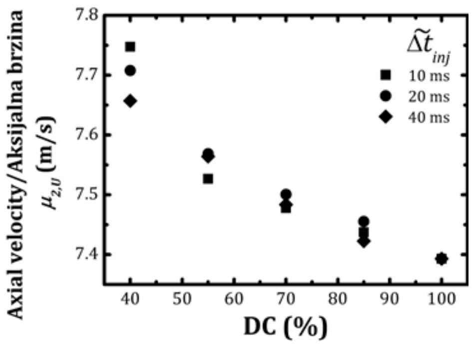


Figure 5. Variation of the second group of the axial velocity distribution ($\mu_{2,U}$) with the duty cycle (DC)

Slika 5. Promjene distribucije aksijalne brzine u drugoj skupini ($\mu_{2,U}$) s radnim ciklusom (DC)

Nonetheless, the magnitude of the measured value is within the range expected for multijet impingement sprays formed from turbulent liquid sheets, since the hydrodynamics of the atomization process has been shown to be similar regardless the number of impinging jets [14]. For N_j = 2 jets, Anderson et al. [15] have provided an empirical correlation for the arithmetic mean diameter as $d_{10} = 2.217 \cdot d_j \left(\mathrm{We}_j f(\theta)\right)^{-0.354}$, where We_j is the Weber number of the jet ($= \rho U_j^2 d_j/\gamma$) and $f(\theta) = \left(1 - \cos(\theta)\right)^{2} \cdot \sin^{-3}(\theta)$. Fig. 6 includes the value obtained for the geometrical configuration of the atomizers used in this work, confirming the similarity in the order of magnitude.

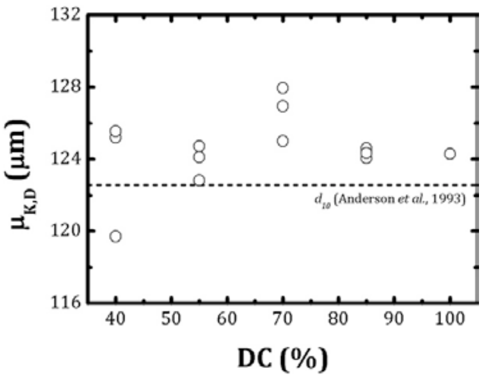


Figure 6. Weighted characteristic mean diameter of droplets ($\mu_{K,D}$) as a function of DC. The dashed line corresponds to the estimation of the arithmetic mean diameter for sprays produced by turbulent sheets formed from the impact of two jets according to Anderson *et al.* [15]

Slika 6. Težinska karakteristika prosječnog promjera kapljica ($\mu_{K,D}$) kao funkcija DC. Isprekidana linija predstavlja procjenu aritmetičke sredine promjera za raspršivače koje proizvode turbulentne ploče formirane utjecajem dva mlaza prema Anderson *et al.* [15]

3.2. Local influence of spray characteristics on liquid deposition and heat transfer

Spray impingement heat transfer events depend on the deposition of the liquid injected on the heated surface and the ability to control it. In previously reported results, if spray impaction is unavoidable, the best heat transfer efficiency for cooling purposes is achieved if a thin liquid film remains present on the heated surface [7]. Consequently, the highest heat transfer efficiencies were obtained with short time intervals between consecutive injection cycles (10 ms).

On the other hand, in terms of predicting the outcome of spray impact, the criteria in the model of Bai *et al.* [16] are used to discern between the basic hydrodynamic mechanisms of:

i) Deposition:
   a. stick ($\mathrm{We}_d \le 2$) and
   b. spread ($20 < \mathrm{We}_d \le \mathrm{We}_c = 1320 \cdot \mathrm{La}_d^{-0.183}$) which contribute to the formation of a liquid film;

ii) and Secondary Atomization:
   c. rebound ($2 < \mathrm{We}_d \le 20$) or
   d. splash ($\mathrm{We}_d > 1320 \cdot \mathrm{La}_d^{-0.183}$), where We_d is the Weber number of droplets, $\mathrm{We}_d = \rho \mu_{K,U}^2 \mu_{K,D}/\gamma$, and La_d is the Laplace number ($\mathrm{La}_d = \rho \gamma \mu_{K,D}/\mu_f^2$, where μ_f is the fluid dynamic viscosity).

These criteria have been applied to drop size and velocity data, and the percentage of drops in each mechanism has been estimated. Fig. 7 shows the effect of the duty cycle (DC) on the efficiency of the heat transfer process (below) and the percentage of droplets in the spray expected to deposit on the impinging surface (above). According to the criteria of Bai *et al.* [16], slightly more than half of the spray droplets are expected to deposit on the surface, and a trend for slightly increasing this fraction or percentage is observed as DC approaches the condition of a continuous spray (DC = 100%).

The evolution of the deposition percentage with DC, observed in Fig. 7, is coherent with the observed fact that a higher DC implies a larger mass flux injected, leading to thicker liquid films and jeopardization of heat transfer [7]. However, while it is evident that a shorter time between consecutive injections improves the heat transfer efficiency, no such trend is observed relative to the fraction of droplets expected to deposit on the surface.

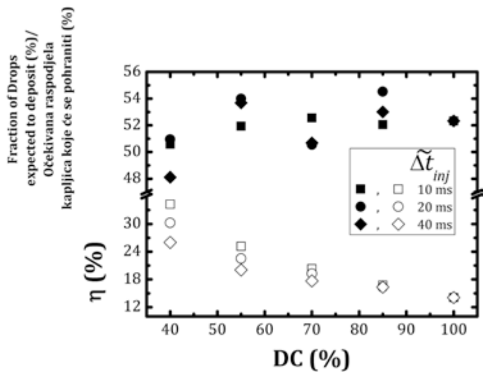


Figure 7. Effect of the duty cycle (DC) on the efficiency and expected deposited fraction of droplets for non-injection times $\left(\widetilde{\Delta t_{inj}}\right)$ of 10, 20 and 40 ms

Slika 7. Utjecaj radnog ciklusa (DC) na učinkovitost i očekivanu pohranu dijela kapljica u vremenu bez ubrizgavanja $\left(\widetilde{\Delta t_{inj}}\right)$ od 10, 20 i 40 ms

On the other hand, the behavioural pattern of the axial velocity with DC, shown in Fig. 5, is similar to the monotonic decrease observed for the heat transfer efficiency in Fig. 7 (bottom). This would be consistent with the fact that impinging droplets are likely to pierce the liquid film, allowing cooler liquid to reach the surface more efficiently, particularly in the cases of thinner liquid films, thus enhancing heat transfer. These results suggest that not only the axial velocity might be a determinant parameter for heat transfer [17], but more so the relation between droplet velocity and a controlled liquid film thickness.

Using the heat transfer data with that of the spray characteristics, a correlation is sought. However, the purpose is not to provide a new empirical correlation *per se*, but rather to physically interpret the value obtained for its constant parameters. In order to distinguish the effects of drop size and velocity, two dimensionless numbers have been used, the Laplace $La_d = Re_d^2/We_d \sim g(D)$ and Capillary $Ca_d = We_d/Re_d \sim g(U)$ numbers. The Nusselt number is defined as $Nu = h_{sc}\mu_{K,D}/k_f$, with h_{sc} as the heat transfer coefficient, $\mu_{K,D}$ the weighted characteristic mean diameter and k_f the liquid thermal conductivity. In Fig. 8, it is observed how heat transfer is higher for the most efficient operating conditions $\left(\widetilde{\Delta t_{inj}} = 10\text{ms}\right)$, while increasing the time between consecutive injection cycles leads to lower heat transfer rates. This evidences the importance of the ability to control the presence of a thin liquid film for spray cooling.

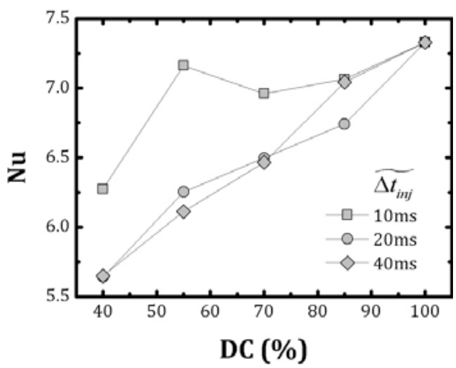


Figure 8. Variation of Nu as a function of the duty cycle (DC) for different non-injection times between consecutive cycles

Slika 8. Promjena Nu kao funkcija radnog ciklusa (DC) za različita vremena bez ubrizgavanja između uzastopnih ciklusa

The La_d and Ca_d numbers have also used weighted characteristic mean parameters ($\mu_{K,D}$ and $\mu_{K,U}$) in their calculation. The empirical correlation has the typical form of

$$Nu = a\,La_d^b\,Ca_d^c \qquad (6)$$

where *a*, *b* and *c* are the correlation constants. Although heat transfer correlations usually use the Prandtl number (Pr), relating the kinematic and thermal diffusivities, the fluid is the same in every experiment, as are the environmental conditions. Therefore, the effect of Pr would be constant and, thus, included in constant *a*.

Using a direct least square method, *b* and *c* are estimated to be negative (see Fig. 9-top), suggesting that by increasing the size, since $La_d >> 1 \wedge b < 0$, heat transfer is jeopardized, while by increasing the axial velocity of impinging droplets, since $Ca_d < 1 \wedge c < 0$, heat transfer is improved. Usually, there is a positive correlation between droplet size and velocity, i.e. larger droplets are less prone to interact with the surrounding environment, and thus, are faster than smaller droplets. Therefore, the constant parameters in this correlation indicate a competition between these two effects. However, Fig. 9 (bottom) shows how the effect exerted by the dimensionless parameter Ca_d, associated with the axial velocity, is more influential relative to the drop size associated with La_d.

An additional point is that faster droplets have greater impact energy and their likely outcome is not to deposit on the surface for cooling purposes, but eventually to trigger secondary atomization mechanisms and generate secondary droplets. In this case, part of the liquid is not in contact with the surface, but eventually deposits at a later time, and since the impact energy of secondary droplets is typically much lower, these are expected to deposit and remove heat by phase-change.

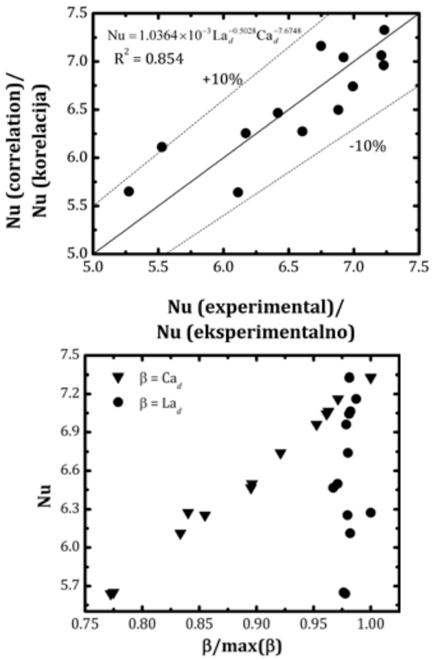


Figure 9. Comparison between Nu obtained experimentally and through an empirical correlation (top); and influence of dimensionless numbers Ca_d and La_d on the Nusselt number (bottom)

Slika 9. Usporedba između Nu dobivene eksperimentalno kroz empirijske korelacije (gore); i utjecaj bezdimenzijskih brojeva Ca_d and La_d na Nusseltov broj (dolje)

3.3. Toward intelligent thermal management

In order to have an intelligent thermal management, it is important to devise a strategy that allows an active control over the cooling process. Pavlova *et al.* [4] have explored the flapping of a spray produced by synthetic jets, using piezoelectric actuators, to perform the active control of the spray density upon its impaction, thus, enabling the control of heat transfer in the non-boiling regime. Panão and Moreira [5] proposed an Intermittent Spray Cooling (ISC) strategy, where the parameter controlling heat transfer has been identified as the Duty Cycle ($DC = f_{inj} \cdot \Delta t_{inj} \times 100\%$), through which one may control the time and interaction between consecutive injections. Consequently, a greater or lesser degree of saturation near the liquid-vapour interface can be obtained, influencing the vaporization rate and eventually extracting a greater benefit from phase-change cooling. However, the same *DC* can be obtained with different matches between frequency and duration of injection, therefore, the question remains as to which is the best and most efficient choice. In Panão *et al.* [7], the degree of interaction between multiple consecutive injection cycles has been analyzed by varying the frequency of injection, or the time interval between the end of an injection and the start of the next one, considering also its implications for the efficiency of the cooling process. It has been observed that the highest frequency possible (within the constructive constraints of the electromechanical valve) should be chosen for maximizing heat transfer.

The way in which the cooling liquid is directly spread throughout the heated surface implies a careful choice of the atomization strategy. A tailored spray would break into small, well dispersed, droplets, which, upon impact, are more likely to deposit on the surface, depending on the hydrodynamic and heat transfer impinging mechanisms [11]. In Panão *et al.* [14], a strategy has been studied which produces a spray through the single-point impact of multiple cylindrical jets, thus referred as multijet impingement atomization. In this kind of atomization, the collision between two or more jets generates a liquid sheet, which destabilizes while developing due to the interaction between inertial and surface tension forces with the surrounding air, disintegrating into droplets at the liquid-air boundary. For the characterization of the spray reported in [14], its potential applicability to microprocessors cooling has been assessed in Panão *et al.* [6]. Moreover, the ability of using the spray intermittency for controlling surface temperature has been demonstrated in Panão *et al.* [18], although within the microprocessor context where the heat fluxes are much lower, but one should not expect a significant difference if applied to power electronic devices.

Furthermore, it has already been mentioned that two-phase convective cooling (such as spray cooling) has been claimed as the best choice for developing a thermal management system for cooling IGBT power modules used in power electronics, because it boosts power density while keeping the volume/weight/cost as low as possible. The justification for this claim lies in the benefit of removing heat through phase-change. Therefore, how does intermittent spray cooling (which may also work in a continuous mode) compare with systems based on continuous sprays reported in the literature?

The χ-parameter is used in this comparison because it quantifies the benefit of phase-change and allows for comparison between different cooling configurations, using different liquids and atomization strategies. A preliminary analysis of the results reported in the literature shows that some dissipated heat fluxes may be very high, but it does not mean that such an outcome is related to the benefit of phase-change. Namely, when the criterion defined in case 3 of the solution presented in section 2.3 is applied, some results evidence that those high dissipated heat fluxes are not the result of phase-change cooling, but of the larger amount of sensible heat removed at a given operating condition. If the aforementioned criterion is expressed as $\frac{Ja(1-\eta)}{\eta} \leq 1 \vee \frac{Ja(1-\eta)}{\eta} > 1$, the first case indicates benefit from phase-change, and thus a dominant two-phase convective cooling, while the second case indicates that phase-change is mitigated and single-phase cooling becomes the dominant heat transfer mechanism (see Fig. 10).

It is noteworthy from Fig. 10 how most experiences which lead to the mitigation of phase-change have water as the cooling liquid, except for two conditions in the work of Chen *et al.* [19], which differ from the remainder by the larger than average size of the spray droplets. This suggests that dielectric fluids are more appropriate for the direct cooling of power electronic devices.

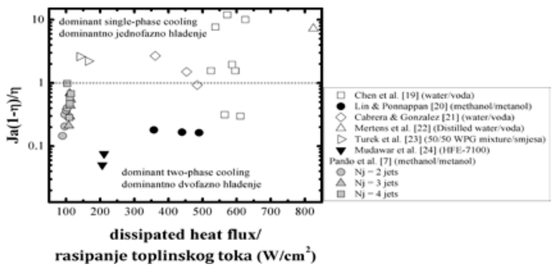


Figure 10. Comparison between the dissipated heat flux and the criterion $\frac{Ja(1-\eta)}{\eta}$

Slika 10. Usporedba između rasipanja toplinskog toka i kriterija $\frac{Ja(1-\eta)}{\eta}$

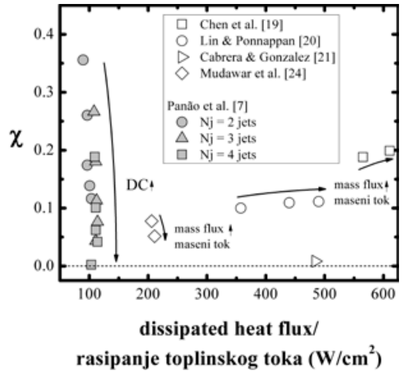


Figure 11. Comparison between the dissipated heat flux and the χ-parameter

Slika 11. Usporedba između rasipanja toplinskog toka i parametra χ

If we now consider only the cases which benefit from phase change $\frac{Ja(1-\eta)}{\eta} \leq 1$ and compare the amount of dissipated heat flux with the χ-parameter (see Fig. 11), assuming the worst scenario for phase-change cooling where all the liquid injected is accumulated at the surface, $\alpha = 1$ (in reality, if $\alpha < 1$, χ would increase), several considerations can be made:

- a higher heat dissipation rate does not imply a larger benefit from phase-change;
- except for a slight improvement in Mudawar *et al.* [24], in continuous spray cooling, variations in the flow rate [19, 20] do not produce any significant effect on the benefit of phase-change. Namely, it is suggested that in intermittent spray cooling, changing the Duty Cycle, and, consequently, changing the degree of interaction between consecutive cycles, allows for the same heat dissipation ability, but increasing the benefit extracted from phase-change. Namely, it is suggested that a lower DC, implying more time between consecutive cycles relative to the injection time, allows a less saturated environment at the liquid-vapour interface and promotes heat exchanges through the latent heat of vaporization.

4. Concluding remarks

The argument in this paper is that thermal management plays a crucial role in the development of the powertrain in electric vehicles. Namely, the energy demands occurring during power peaks imply that losses in power electronic devices are likely to vary within the vehicle's driving cycle. Therefore, an intelligent thermal management able to efficiently respond to these power peaks is advantageous and the investigation of an intermittent multijet impingement spray for direct cooling purposes constitutes the main motivation for this work. A local analysis is made on the correlation between the characteristics of a multijet impingement spray and the heat transfer that keeps the surface temperature in a steady-state condition at 125ºC. The spray is characterized through a statistical analysis using finite mixtures of weighted Lognormal distributions for describing the polydispersed sizes of droplets and normal distributions for describing their axial velocity component (perpendicular to an impinging surface). The advantage of using this more advanced statistical tool is that one considers the entire distribution in the analysis, instead of its moments alone.

Results for the spray characteristics evidence:

- the presence of three groups of droplets characterizing the spray in every intermittent operating condition. However, the groups with medium and large characteristic sizes are dominant relative to the group of smaller droplets;
- droplets' size polydispersion expressed by the standard deviation of the log-normal is well correlated with the characteristic size as $\sigma_{K,D} = 7.9264\mu_{K,D}^{-0.615}$ ($R^2 = 0.996$);
- droplets' axial velocity is mainly constituted by a group around 86% of the jet velocity (8.8m/s), and does not significantly vary with the duty cycle (DC).

The characteristics of droplets have been measured for the same operating conditions of previously reported heat transfer experiments, in order to evaluate their correlation, as well as the expected outcome of impact. Results evidence that multiple injection pulses with shorter time intervals between consecutive cycles induce a greater importance to the relation between droplets' axial velocity and the control of the liquid film thickness for heat transfer enhancement.

Moreover, if the advantage of spray cooling is to benefit from phase-change, it is important to devise a parameter which allows the evaluation of such benefit and enables the comparison of different spray configurations, liquids and hydrodynamics on spray impaction, including the implications of the degree of liquid accumulation on the surface. This χ-parameter has been devised and has been found to depend on the cooling efficiency η, accumulated mass flux α and the Jakob dimensionless number, which relates the heat associated with the subcooling degree with the latent heat.

Given the body of experimental work reported in the literature, a comparison is made between those studies addressing the issue of high heat fluxes in power electronics. According to the analysis of χ, not all benefit from phase-change, and of those that benefit, only the intermittent spray cooling strategy has the ability to control that benefit through the duty cycle. Namely, with a lower degree of interaction between consecutive injection cycles, the system benefits more from phase-change cooling, thereby demonstrating the potential use of intermittent spray cooling for developing an intelligent thermal management for power electronics devices in full electrical vehicles.

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REFERENCES

[1] JAMES, P.; FORSYTH, A.; CALDERON-LOPEZ, G.; PICKERT, V.: *DC-DC converter for hybrid and all electric vehicles*, Proceedings EVS-24, The 24th International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium and Exhibition, Stavanger, Norway, May 13-16, 2009.

[2] CHAMUND, D.J.; COULBECK, L.; NEWCOMBE, D.R.; WAIND, P.R.: *High Power Density IGBT Module for High Reliability Applications*, Power Electronics and Motion Control Conference,. IPEMC '09. IEEE 6th International, 2009.

[3] WOLMARANS. J.J.; GERBER, M.B.; POLINDER, H.; DE HAAN, S.W.H.; FERREIRA, J.A.; CLARENBACH, D.: *A 50kW integrated fault tolerant permanent magnet machine and motor drive*, IEEE Power Electronics Specialists Conference, *PESC* 2008.

[4] PAVLOVA, A.A.; OTANI, K.; AMITAY, M.: *Active performance enhancement of spray cooling*, Int J Heat and Fluid Flow, 29 (2008), 985-1000.

[5] PANÃO M.R.O., MOREIRA A.L.N., *Intermittent spray cooling: a new technology for controlling surface temperature*, Int J Heat and Fluid Flow, 30 (2009), 117-130.

[6] PANÃO, M.R.O.; MOREIRA, A.L.N.; DURÃO, D.F.G.: *Thermal-fluid assessment of multijet atomization for spray cooling applications*, Energy, 36 (2011), 2302-2311.

[7] PANÃO, M.R.O.; CORREIA, A.M.; MOREIRA, A.L.N.: *High-power electronics thermal management with intermittent multijet sprays*, Applied Thermal Engineering 37 (2012), 293-301.

[8] PANÃO, M.R.O.; MOREIRA, A.L.N.; DURÃO, D.F.G.: *Statistical analysis of spray impact to assess fuel mixture*

preparation in IC engines, Fuel Processing Technology, doi:10.1016/j.fuproc.2012.07.022 (2012).

[9] BABINSKY, E.; SOJKA, P.E.: *Modeling drop size distributions*, Prog. Energy and Combustion Science, 28 (2002), 303-329.

[10] PANÃO, M.R.O.; RADU, L.: *Advanced statistics to improve the physical interpretation of atomization processes*, submitted to International Journal of Heat and Fluid Flow (2012).

[11] MOREIRA, A.L.N.; MOITA, A.S.; PANÃO, M.R.O.: *Advances and challenges in explaining fuel spray impingement: How much of single droplet impact research is useful?*, Progress in Energy and Combustion Science, 36 (2011) 5, 554-580.

[12] RINI, D.P.; CHEN, R.-H.; CHOW, L.C.: *Bubble Behavior and Nucleate Boiling Heat Transfer in Saturated FC-72 Spray Cooling*, J. Heat Transfer, 124 (2002) 1, 63-72.

[13] ZHAO, R.; CHENG, W.; LIU, Q.: *Study on heat transfer performance of spray cooling: model and analysis*, Heat Mass Transfer, 46 (2010), 821-829.

[14] PANÃO, M.R.O.; MOREIRA, A.L.N.; DURÃO, D.F.G.: *Transient analysis of intermittent multijet sprays*, Experiments in Fluids, 53 (2012), 105-119.

[15] ANDERSON, W.; RYAN, S.; SANTORO, R.: *Spray formation processes of impinging jet injectors*, NASA Prop Eng Res C 2 (1993), 69–74.

[16] BAI, C.; RUSCHE, H.; GOSMAN, A.: *Modeling of gasoline spray impingement*, Atomization and Sprays 12 (2002), 1–27.

[17] ARCOUMANIS, C.; CHANG, J.-C.: *Heat transfer between a heated plate and an impinging transient diesel spray*, Experiments in Fluids, 16 (1993), 105-119

[18] PANÃO, M.R.O.; GUERREIRO, J.P.P.V.; MOREIRA, A.L.N.: *Microprocessor Cooling based on an Intermittent Multi-jet Spray System*, International Journal of Heat and Mass Transfer 55 (2012), 2854-2863.

[19] CHEN, R.-H.; CHOW, L.C.; NAVEDO, J.E.: *Effects of spray characteristics on critical heat flux in subcooled water spray cooling*, International Journal of Heat and Mass Transfer, 45 (2002), 4033-4043.

[20] LIN, L.; PONNAPPAN, R.: *Heat transfer characteristics of spray cooling in a closed loop*, Int J Heat and Mass Transfer, 46 (2003), 3737-3746.

[21] CABRERA, E.; GONZALEZ, J.E.: *Heat flux correlation for spray cooling in the nucleate boiling regime*, Experimental Heat Transfer, 16 (2003), 19-44.

[22] MERTENS, R.G.; CHOW, L.; SUNDARAM, K.B.; CREGGER, R.B.; RINI, D.P.; TUREK, L.; SAARLOOS, B.A.: *Spray cooling of IGBT devices*, J Electronic Packaging, 129 (2007), 316-323.

[23] TUREK, L.J.; RINI, D.P.; SAARLOOS, B.A.; CHOW, L.C.; *Evaporative spray cooling of power electronics using high temperature coolant*, 11th Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems, ITHERM, 346-351, 2008

[24] MUDAWAR, I.; BHARATHAN, D.; KELLY, K.; NARUMANCHI, S.: *Two-Phase Spray Cooling of Hybrid Vehicle Electronics*, IEEE Trans. Comp. & Pack. Tech., 32 (2009), 501-512.