MULTIJET ATOMIZATION AND ENERGY EFFICIENCY TOWARD INTELLIGENT THERMAL MANAGEMENT SYSTEMS

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Abstract: Harsh environments and different driving patterns induce variability in the heat dissipation of power electronic devices used in electric vehicles posing serious challenges to existing thermal management technologies. Direct liquid cooling using sprays appears to be most promising because it allows a two-phase convective boiling, taking greater benefit from phase-change in the cooling process. However, direct spray cooling depends on the atomization strategy and this work reports the investigation made on the hydrodynamic mechanisms which form multijet sprays through the simultaneous single-point impact of a number of cylindrical jets, and its advantages for high-heat flux cooling. Moreover, while most spray cooling research focus on the particular case of continuous sprays, here, the more general case of intermittent sprays is considered. The effect of the spray intermittency and number of impinging jets on the energy efficiency is analyzed and the benefit retrieved from phase-change is evaluated. Finally, a comparison is made with other works exploring the limitations and advantages of intelligent thermal management using intermittent multijet sprays.

1. Introduction

The development of cheap and highly efficient electrical machines, 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. This implies the application of thermal management to overcome eventual limitations imposed on power density required by electrical machines, to increase its lifetime and reliability (Wolmarans et al., 2008), while keeping an overall low system weight and volume. In this sense, thermal management becomes one of the most serious technological challenges for significant advances toward a greater implementation of the full electric vehicle in the automotive mass-production market.

It is possible to identify two main research streams related with the development of appropriate thermal management systems for electrical vehicles: 1) urban mobility and; 2) thermal control technologies.
Urban mobility is associated with traffic flows, which are known to have become a major source of carbon emissions into the atmosphere, therefore, technological advancements to improve the competitiveness of the electric vehicle, compared to those using internal combustion engines, provide a significant contribution in its reduction. Urban mobility patterns are usually characterized through driving cycles and it has been shown that standardized patterns do not reflect the real behavior of vehicles in their normal use, therefore, implying that real driving acquisition of velocity transients is required to determine the effective power flows of the powertrain in order to have a more accurate correlation between them (Villatico & Zuccari, 2008). Also, driving behavior induces stochastic variations in urban driving cycles and, consequently, on the powertrain performance (Eriksson & Jacobson, 1999). Therefore, to improve the powertrain performance of an electric vehicle, developing an intelligent thermal management of power electronics devices on which the performance of the electrical machine rely, one must take into account the close-loop driver-vehicle cooperative characteristics, similar to what has been done for safety systems (Inata et al., 2008). The relation between urban mobility patterns, driving behavior dependency and their implications for the thermal loads induced in power electronic devices, could be expressed by thermal driving cycles, corresponding to the heat generated on these devices along the vehicle’s driving cycle. The characterization of such duty cycles is still lacking in the literature available, but it is a necessary input to the development of thermal control technologies with intelligent thermal management. Nonetheless, the present work is focused on the second main research stream.

Thermal control or management technologies applied to maintain the operating temperature in power electronics associated with electrical machines depends not only on the cooling systems used, but also, and no less important, on the thermal resistance between the heat sink and its source. At this time, the main technological barrier is identified with the ability to remove heat fluxes above 250-300W/cm² while maintaining the operating surface temperature of power electronic devices below 125°C. However, the research on urban mobility in terms of thermal driving cycles suggests that transient heat loads are expected, thus not only the magnitude, but also the unsteadiness of heat dissipation becomes an important technological barrier, although it has not been considered in the literature as it should. This is why overcoming these barriers requires innovating approaches for cooling technologies, but also an intelligent thermal management approach.

This work is motivated by the possibility that research and design such intelligent thermal management is at hand. In fact, a basic rule of thermal management states that thermal resistance is kept small either by decreasing the heat path length, or increasing the heat dissipation area (März, 2003). In the later case, increasing the heat dissipation area would promote a better heat spreading, but at the cost of increasing the cooling system volume, and possibly its weight.
Also, the ideal case would be to “eliminate” the heat path length. Therefore, the following section is dedicated to a brief review of the work report on direct liquid cooling using sprays. However, considering that there are several atomization strategies, section 3 is particularly focus multijet atomization based on previous experimental work. Section 4 is dedicated to the application of intermittent multijet sprays to high-heat flux cooling and compares the approach followed with other works reported in the literature considering continuous sprays.

2. Direct spray cooling

Direct liquid cooling has been proposed as an alternative cooling technology which eliminates conductive resistances of intermediate layers, allowing a closer packaging of high heat flux chips, thus substantially reducing the weight and volume of the cooling system. Mudawar et al. (2009) have applied direct spray cooling on the power electronics context and were able to achieve heat fluxes slightly above 250W/cm² demonstrating the feasibility of the concept. Moreover, if a comparison is made relatively to the order of magnitude of the convection heat transfer coefficient associated with direct liquid cooling, Mudawar et al. (2009) have observed that it is 10 times that of liquid force convection, 10² of liquid natural convection and 10³ that of air forced convection. Also Turek et al. (2008) have used an evaporative spray cooling nozzle array applied to an IGBT-based inverter, capable of removing up to 140W/cm² while its operating temperature is kept slightly under 125°C. Using an air-water (distilled) spray as the best solution compared to similar ones, Mertens et al. (2007) were able to operate IGBT devices at 125°C with slightly less than 500W/cm². The air-water spray impinged onto a 0.5mm copper heat sink to avoid device failure. Although the heat fluxes obtained with distilled water are high, there is still the risk of contamination and the freezing point is 0°C compared to the negative values of dielectric fluids, which turns the later a more safe option, especially considering the possible harsh environments experienced by power electronics in electrical machines. One of the other means of enhancing heat transfer associated with spray impact is the modification of the impinging surface. For example, structured surfaces allow increasing the effective heat transfer coefficient on almost one order of magnitude (Sodtke and Stephan, 2007).

However, none of the works reported so far took 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 over droplet density, as suggested by Pavlova et al. (2008), or as a temporal control over the flow rate using an intermittent spray by proper matching the frequency and duration of injection. The second approach allows a cooling system capable of responding to transient heat loads and has been shown to achieve liquid savings up to 90%, for the same efficiencies
reported on continuous spray cooling systems (Panão and Moreira, 2009).

An important part of any spray cooling system is the kind of atomization process used to break the liquid coolant into droplets and scatter them, as uniformly as possible, throughout the cooling area. Since most spray cooling application to power electronics use continuous sprays, usually with pressure atomizers, the atomization process can only be improved by decreasing the nozzle hole diameter and increasing the pressure, limiting optimization to those parameters. In previous works, an atomization strategy based on the single-point impact of multiple cylindrical jets (multijet atomization) is explored, which has been shown to produce low-pressure sprays with relatively low momentum droplets, improving the control of deposition rate for cooling purposes (Panão et al., 2009).

Despite these developments, it is still recognized that spray cooling technology is promising for high heat fluxes, but a promise not yet fully realized, and Shedd (2007) suggests that limitations on the current understanding of the associated heat transfer mechanisms might be the cause of this, namely, in terms of the energy efficiency of the process, which is addressed in this paper.

3. Multijet atomization

The multijet atomization strategy consists in producing a spray from the single-point impact of multiple cylindrical jets from which a liquid sheet develops, breaks into ligaments and these fragment into droplets. Most works are based on the impingement of two jets, and little is reported on the use of more than 2 jets. Only recently in Panão et al. (2011a), it has been reported that one should not expect significant changes in the hydrodynamics mechanisms when the number of impinging jets increases (Fig. 1).

![Fig. 1 Detail of the prototype atomizers with 2, 3 and 4 impinging jets.](image)
For the turbulent liquid sheet regime (Li and Ashgriz, 2006), Fig. 2 shows that surface waves appear in multijet sprays regardless the number of impinging jets \( (N_j) \), and two typical sources of droplet formation (detached and edge ligaments) have been visualized, although edge ligaments are less visible for \( N_j = 4 \).

![Fig. 2](image-url) Identification of the main hydrodynamic structures in multijet sprays with 2, 3 and 4 impinging-jets.

In Panão and Radu (2011), these sprays have been analyzed using a Bayesian approach to find the mixture of lognormal distributions which best describe the drop size distribution of these multijet sprays. By mixture one means the weighted linear combination of lognormal distribution functions, \( f_{LN}(\mu_k, \gamma_k) \), where \( \mu_k \) is the characteristic size of the distribution and \( \gamma_k \) the standard deviation. Thus the mixture distribution of \( K \) functions corresponds to

\[
f_{LN, mix} = \sum_{w=1}^{K} \eta_w f_{LN} \left( \mu_w, \gamma_w \right)
\]

In Panão and Radu (2011), four groups of droplets have been identified (\( K = 4 \), see Fig. 3), but through a physical analysis only two mechanisms have been associated with atomization mechanisms and, consequently, to the instabilities which fragmented ligaments into droplets (capillary and Kelvin-Helmholtz).

![Fig. 3](image-url) Discrete drop size distributions for the atomizers with \( N_j = 2, 3 \) and 4 impinging jets and the best mixture of lognormal distribution functions with \( K = 4 \).
Fig. 4 Groups of droplets identified for each multijet spray using a Bayesian approach with a Markov chain Monte Carlo algorithm (Panão and Radu, 2011).

For the capillary or Rayleigh instability, the maximum growth rate of the instability occurs when the product of the wave number \(k\) and the ligament radius \(\xi\) is equal to 0.697 (Ashgriz and Yarin, 2011). The Kelvin-Helmholtz instability occurs when the interaction between a liquid sheet and the surrounding air leads to its disintegration into ligaments and the wave number of those instabilities is expressed as (see Senecal et al., 1999)

\[
\frac{\pi}{6} d_o^3 = \frac{4}{\xi} \text{capillary instability} \quad C \quad d_{D,C}/\xi_C = 1.891 \quad \text{and for the Kelvin-Helmholtz} \quad KH \quad d_{D,KH}/\xi_{KH} = 1.882, \quad \text{thus the relation between} \quad d_{D,C}/d_{D,KH} \sim \xi_C/\xi_{KH}.
\]

It is reasonable to assume that the ligament diameter from a capillary instability is of the same order of magnitude as the rim diameter of the turbulent liquid sheet \(d_r\), \(\xi_C \sim d_r\), and from the visualization made (Fig. 5) \(d_r\) has been estimated to be 40% of the jet diameter \(d_j\), thus

\[
\xi_C \sim 0.4 d_j \tag{1}
\]
Fig. 5 Detail of the jet diameter and indication of the average size of the bounding rim.

Relatively to the ligaments formed by the Kelvin-Helmholtz instability, the first step is to estimate if the waves in the turbulent liquid sheet are within the long or short wave regime. Koo argues that when the surrounding gas Weber number, $We_g = \rho_g U_s^2 (\bar{h} / 2) / \sigma_L$, is less that $27/16$, long waves tend to grow and breakup the liquid sheet (Koo, 2003), where $U_s$ is the average liquid sheet velocity and $\bar{h}$ the average sheet thickness at breakup. In the case of long wave growth instabilities, Senecal et al. (1999) argue that ligaments are formed from tears in the sheet twice per wavelength, therefore,

$$\xi_{KH} = \sqrt{\frac{4\bar{h}}{k_s}} \quad (2)$$

where $k_s$ is the most unstable long wave growth given by $k_s = \rho_g U_s^2 / (2\sigma)$. Following the physical modeling of Li and Ashgriz (2006), the average sheet thickness obtained by averaging the sheet thickness from the edge of the impact region ($r_i$) to the edge of the sheet ($r_e$) as

$$\bar{h} = \frac{d_j}{2\pi} \int_0^\pi hr \left( \frac{d_j}{2} \right)^2 \ln \left( \frac{r_e}{(d_j/2)} \right) \ln \left( \frac{r_i}{(d_j/2)} \right) d\phi$$

(3)

where the parameters in eq. (3) are given by $r_e / (d_j/2) = 1 / \sin(\theta)$

$$r_e / (d_j/2) = We_j \left( \frac{hr}{(d_j/2)^2} \right) \sin(\psi) \frac{1}{4}$$

with $We_j = \rho_L U_j^2 d_j / \sigma_L$ as the jet Weber number,

$$\frac{hr}{(d_j/2)^2} = \beta e^{\theta(1-\psi/\pi)} \frac{e^\theta - 1}{e^\theta - 1}$$

where $\beta$ is determined according to

$$\cos(\theta) = \left( \frac{e^\theta + 1}{e^\theta - 1} \right) \frac{1}{1 + (\pi / \beta)^2}$$


, and finally
\[
\frac{h_r}{(d_j/2)^2} = \frac{\beta e^{\theta(1-\phi/x)}}{e^\theta - 1} \quad \text{and} \quad \psi = \frac{\pi}{2} e^{-\frac{(2\theta)}{\pi}}
\]

For the multijet sprays considered in this work, \( \theta = \pi/4 \), resulting in \( \beta = 4.74; U_j = 9 \text{ m/s}; d_j = 400 \mu\text{m}; \) and the fluid is methanol with \( \rho_L = 788 \text{kg/m}^3 \) and \( \sigma_L = 22.4 \text{ mN/m} \). The surrounding gas is air at ambient pressure, so it is assumed that \( \rho_a = 1.2 \text{ kg/m}^3 \). Also, the liquid sheet average velocity is considered of the same order of magnitude as the jet velocity, \( U_s \sim U_j \). Therefore, the ratio between equations (1) and (2) for these experimental conditions is \( \xi_c / \xi_{KH} = 1.81 \). In fact, the ratio between the characteristic diameters of droplets in groups 3 and 4, as depicted in Fig. 4, results in \( \mu_4 / \mu_3 \approx 1.78 \), thus, there is reasonable evidence suggesting that the larger droplets in group 4 might have been generated by a capillary instability, while droplets in group 3 were generated through a Kelvin-Helmholtz instability.

With these multijet sprays made of small and relatively slower droplets, Panão et al. (2011a) have shown that it is more likely that these deposit on the surface for cooling purposes, than generate a secondary atomization. Additionally, the efficiency of depositing liquid onto a solid surface depends on the accurate control of the flow rate and a way to control it intelligently, while keeping pump pressure constant, is to spray the liquid intermittently by proper matching the frequency with the duration of injection. The implications of this intermittency for heat transfer is the subject of the following section.

4. Effect of spray intermittency on high-heat flux dissipation

One of the main advantages of an intermittent spray cooling system is the ability to remove part of the vapor from the liquid-gas interface in the time between consecutive injections. This leads to a less saturated environment, thus increasing the efficiency of the cooling process. However, it is worth questioning if this is so, therefore, in Panão et al. (2011a), a series of experiments have been conducted where the time between consecutive injections is the variable parameter (see Fig. 6). Additionally, the operating condition desired is the maximum heat flux that it is possible to remove while keeping the surface temperature slightly below the threshold of 125°C, above which IGBT-based devices experience a thermal shutdown.
An experimental setup has been designed to dissipate heat fluxes up to 270 W/cm². The heating component consists in a copper cylindrical block \((b)\) with a machined upper square surface \((A)\) of 2×2 cm², a total block volume of 85.8 cm³, with thermophysical properties of: density \(\rho_b = 8920\) kg·m⁻³; specific heat \(C_{p,b} = 380\) J·kg⁻¹K⁻¹; and thermal conductivity \(k_b = 401\) W·m⁻¹K⁻¹. In the bottom part of the cylinder, four electrical cartridge heaters of 350 W connected in parallel provide the desired heat flux range. The cartridge heaters are connected to an AC potentiometer allowing the regulation of the input voltage and, consequently, control the imposed heat flux. In order to insulate the structure and minimize heat losses, the test surface is wrapped in a silicone glass G7 polymer and the rest of the copper cylinder is covered with glass wool. All these components are encapsulated in a stainless steel structure (Fig. 7). The surface temperature is an extrapolation from the value measured by a K type thermocouple embedded \(\delta_Z = 1.5\) mm below the top surface assuming unidirectional heat conduction.
The experimental procedure consists in heating the surface with a certain imposed heat flux \( \dot{q}_w'' \) until the surface temperature is above 150ºC. Afterwards, the injection begins until it stabilizes in the resulting operating temperature \( T_{op} \) for a certain intermittent condition. If \( T_{op} \) has not reached yet the threshold of 125ºC, \( \dot{q}_w'' \) is increased and a new test is performed. The final analysis considers the maximum values for \( \dot{q}_w'' \) with \( T_{op} \leq 125 \)ºC. In the present work, the analysis focus on the energy efficiency \( \eta \) of the cooling process defined by

\[
\eta = \frac{\dot{q}_w''}{\dot{m}_{inj}'' \left( c_{p,L} \left( T_b - T_f \right) + h_{fg} \right)}
\]

where \( \dot{m}_{inj}'' = DC \cdot \rho_{L} \dot{V}_{inj} \) is the mass flow rate depending on the Duty Cycle, \( C_{p,L} \) is the liquid specific heat, \( T_b \) the boiling temperature, \( T_f \) the fluid temperature and \( h_{fg} \) the latent heat of vaporization. For methanol at 25ºC in an atmospheric environment, \( \rho_{L} = 786.3 \text{ kg·m}^{-3} \), \( C_{p,L} = 2.534 \text{ Kj·Kg}^{-1}\text{K}^{-1} \), \( T_b = 64.5 \)ºC and \( h_{fg} = 1100 \text{ kJ·K}^{-1} \). The energy efficiency results for the three multijet sprays with \( N_j = 2, 3 \) and 4 impinging jets depicted in Fig. 8 evidence how a shorter time between consecutive injection cycles \( \Delta t_{inj} = 10 \text{ ms} \) for the same mass flow rate leads to an increase of \( \eta \), especially for the lower DC values. Obviously, as DC increases and approaches the particular case of a continuous spray \( (DC = 100\%) \), the efficiency converges for the three times between consecutive injections considered. Moreover, when the atomizers are compared,

\[
\frac{\partial \eta}{\partial N_j} < 0
\]

which is justified by the increase in the mass flow rate

\[
\frac{\partial \dot{m}_{inj}''}{\partial N_j} > 0
\]
with the number of impinging jets, since the jet velocity (and consequently the jet Reynolds number) has been maintained between atomizers on the assumption of similar conditions for atomization of the liquid injected. Therefore, the main outcome of this analysis is that cooling efficiency improves when a larger pulse is distributed by small ones while keeping the mass flux constant through an increase of the injection frequency.

![Diagram](image)

**Fig. 8** Energy efficiency as a function of the Duty Cycle (DC) in the atomizers with \( N_j = 2, 3 \) and 4 impinging jets for different time intervals between consecutive injections.

However, in order to explain this assessment, the spray impaction on the heated surface has been visualized and the results depicted in Fig. 9 (Panão et al., 2011b). The first observation relatively to the first image at the electronic start-of-injection shows how the surface is dry at the beginning of each injection cycle when \( \Delta t_{\text{inj}} = 40 \text{ ms} \) while a liquid film is present when the mass injected in that single pulse is distributed by the four pulses when \( \Delta t_{\text{inj}} = 10 \). Moreover, the last image for the case with \( \Delta t_{\text{inj}} = 10 \text{ ms} \) captured at 10 ms after the end-of-injection is equivalent to the first, showing that multiple pulses generate the permanent presence of a thin liquid film and that such output is essential for the efficiency of the cooling process.

Additionally, when there is more time between consecutive injections (\( \Delta t_{\text{inj}} = 40 \text{ ms} \)), the liquid film deposited has more time to vaporize leading to a dry surface condition and, consequently, if there is no film to cool the surface, its temperature starts to increase leading, not only to a lower cooling efficiency, but also to a higher thermal stress in the surface material of the power electronic component, which might induce some undesired damage.
Fig. 9 Images of the surface condition for the multijet spray with $N_j=2$ at: i) the electronic start-of-injection; ii) the first image showing the incoming spray; iii) and the end-of-injection; iv) and 10 ms after the end-of-injection.

Furthermore, at 10 ms after the end of inject, a thicker liquid film is evident with $\Delta t_{inj} = 40$ ms, therefore, it is likely that phase-change is mitigated, justifying once more the decrease in the energetic efficiency of the cooling process.

When the three atomizers are compared for the intermittent condition with the highest cooling efficiency (DC = 40%), one observes the presence of a thicker liquid film as $N_j \rightarrow 4$, justifying again the efficiency decrease through the mitigation of phase-change induced by the mass flux increase, as also reported by other authors (see Moreira et al., 2010).

Fig. 10 Comparison between the results of the cooling exerted by the three atomizers at the most efficient condition with DC = 40%, evidencing the presence of a thicker liquid film as $N_j \rightarrow 4$. 
It should be emphasized at this point that most experimental research in spray cooling for power electronic devices is made with continuous sprays, which is a particular condition of the more general intermittent spray, since the later can work continuously when DC = 100%. Furthermore, one of the main arguments for the use of spray cooling technologies in thermal management systems is the ability to benefit from phase-change, thus, a more accurate comparison between different experiments should be made in terms of this benefit. In Panão et al., 2011c, a parameter has been devised to quantify such benefit as

$$\chi = \frac{\eta}{\alpha} + \frac{\eta}{\alpha} \left( \frac{\eta}{\alpha} - 1 \right)$$  \hspace{1cm} (5)

where $\eta$ is the cooling efficiency defined in eq. (4), $\alpha$ is the deposition degree of liquid injected onto the impinging surface and $Ja = \frac{C_p \Delta T_{bf}}{h_{fg}}$ is the Jakob number which relates the sensible to the latent heat of vaporization. Considering that the benefit from phase-change parameter varies in the range $0 \leq \chi \leq 1$, Fig. 11 shows that its validation domains depends on $Ja$. Namely, the cooling efficiency $\eta$ cannot exceed the partial/full deposition of liquid on the surface $\alpha$, because it would lead to an amount of heat removed above the maximum physically possible.

![Fig. 11 Benefit from phase-change $\chi$ domain for $Ja = 0.01$, 0.2 and 0.5.](image)

On the other hand, for certain $Ja$ values (e.g. $Ja = 0.5$), it may emerge a region where the partial/full deposition of liquid exceeds the cooling efficiency leading to $\chi < 0$, which physically means that heat transfer is mainly dominated by single-phase. For the operating conditions with $\Delta t_{inj} = 10$ ms where the efficiency is maximum for each atomizer, eq. (5) is used to assess the effect of $N_j$ in terms of the benefit from phase-change. Despite the efficiency deterioration when $N_j$ increases, Fig. 12 (left) suggests that a lower partial deposition of the liquid could be used to compensate this effect. When compared with other authors (see Fig. 12-right), one observes that the level of benefit from phase-change extracted by the multijet spray configuration is similar to the most efficient case from the several reported by other authors using continuous sprays.
Moreover, if the works of Lin and Ponnappan (2003), and Mudawar et al. (2009) are compared with intermittent multijet sprays in terms of the correlation between $\chi$ and the amount of thermal energy removed by the mass of liquid injected to control the surface temperature defined as $e_*^c = h_c / m_f$ (see Fig. 13), for similar $\chi$-values, Mudawar et al. (2009) removes less thermal energy probably because the fluid (HFE-7100) has a lower latent heat of vaporization ($h_{fg}$), while Lin and Ponnappan (2003) removes more heat also using methanol as in the multijet sprays experiments. The underlying reason could be attributed to the spray configuration used which considered overlapping sprays. Nonetheless, intermittent multijet sprays have shown to benefit more from phase-change when lower DCs are used and, henceforth, should be considered a more advantageous strategy and general approach to transient cooling than continuous sprays, especially for the development of intelligent thermal management systems.

![Diagram](image-url)

**Fig. 12** Benefit of phase-change $\chi$ as a function of the deposition degree on the surface $\alpha$ for: i) the most efficiency condition (DC = 40%) comparing between atomizers (left); ii) the condition of continuous sprays comparing with other authors (right).

![Diagram](image-url)

**Fig. 13** Benefit from phase-change $\chi$ as a function of the specific cooling energy flux removes from the surface comparing intermittent multijet sprays with configurations for the particular case of continuous spray reported by other authors.
5. Conclusions

The challenges posed by thermal management in power electronic devices used in full electric vehicles imply the development of new and more efficient cooling technologies to boost power supply without a substantial increase of the associated volume/weight/cost of cooling systems. Direct liquid cooling using sprays is evermore recognized as the most promising option because it significantly reduces the heat path length. However, this thermal management approach depends on the atomization method used for delivering liquid to control the surface temperature of the power electronic device. In this work, a multijet atomization strategy is explored has an efficient way of producing finely and relatively slow sprays, which more likely deposit on the surface for cooling purposes.

A multijet spray is formed by the simultaneous single-point impact of \( N_j \) cylindrical jets, but since most studies focus on the impact of two-jets, here, the atomization made with more than 2 jets is investigated. Moreover, instead of following the particular case of injecting liquid continuously onto the heated surface, our approach is more general and intermittent sprays are considered instead. The analysis reported focus on the energy efficiency of intermittent multijet sprays and compares the cases with 2, 3 and 4 impinging jets. Additionally, an analysis based on the benefit taken from phase-change is performed and used to compare with other works reported in the literature.

The energetic efficiency of intermittent multijet sprays depends on the percentage of time the injection event represents within the entire cycle (Duty Cycle, DC), and such efficiency deteriorates while approaching the condition of a continuous spray (DC \( \rightarrow \) 100%). For a certain mass flux (depending on DC), the highest cooling efficiency depends on distributing the mass flux injected throughout the operating time, implying shorter times between consecutive injections in order to allow the presence of a thin liquid film and avoid dry/wetted surface conditions which induce larger and probably more damaging thermal stresses on the impact surface. Finally, when the cooling needs are fulfilled by lower DCs, the system is benefiting more from phase-change than current systems injecting continuously. This ability to electronically control de cooling process by adjusting the DC relatively to the heat dissipation requirements at the most efficient operation condition allows the development of intelligent thermal management for the improvement of power supply, lifetime and reliability of power electronic devices in full electric vehicles.

6. References

Eriksson, A., Jacobson, B. 1999. Efficiency comparison between FC and ice in real
Based on Database of Personal Mobility Driving in Urban Area, International
Conference on Control, Automation and Systems, Korea.
Koo, J.Y. 2003. An overview of liquid spray modeling formed by high-shear
nozzle/swirler assembly, KSME International Journal, 17, 726-736.
Li, R., Ashgriz, N. 2006. Characteristics of liquid sheets formed by two impinging
jets, Physics of Fluids, 18, 087104.
International Conference on Industrial Technology, 2, 1196-1201.
Mertens, R.G., Chow, L., Sundaram, K.B., Cregger, R.B., Rini, D.P., Turek, L.,
316-323.
in explaining fuel spray impingement: How much of single droplet impact
research is useful?, Progress in Energy and Combustion Science, 36, 554-580.
Mudawar I., Bharathan D., Kelly K., Narumanchi S., 2009. Two-Phase Spray
512.
for controlling surface temperature, International Journal of Heat and Fluid Flow,
30, 117-130.
intermittent multijet sprays, Experiments in Fluids, accepted for publication.
thermal management with intermittent multijet sprays, Applied Thermal
Engineering (submitted for publication).
management for full electric vehicles, Proceedings of the 6th Dubrovnik Conference
processes, Physics of Fluids, submitted for publication.
for spray cooling, 11th International Conference on Liquid Atomization and Spray
Systems (ICLASS), Vail-Colorado, USA.
Pavlova, A.A., Otani, K., Amitay, M. 2008. Active performance enhancement of
Senecal, P.K., Schmidt, D.P., Nouar, I., Rutland, C.J., Reitz, R.D., Corradini, M.L.