TIME RESOLVED HEAT TRANSFER CHARACTERISTICS OF AN IMPINGING GASOLINE SPRAY

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ABSTRACT

The present paper reports part of an experimental study conducted to deepen knowledge on the thermal-and fluid dynamic interaction mechanisms of gasoline sprays impacting onto interposed surfaces in spark ignition engines with port fuel injection systems. The experiments consider a simplified geometry, which includes a PFI injector spraying gasoline against a flat heated surface. The measurements reported here were conducted to quantify the effects of engine operation conditions on the regimes of heat transfer.

The characteristic thermal parameters of the thermodynamic system spray/target-surface, such as the Critical heat flux and the Leidenfrost temperature, were measured and shown to depend on the frequency and duration of injection as well as on the pressure of injection. The experiments reported here emphasize the effects of the frequency of injection. Analysis further suggests that pulsed sprays have the capability of removing large amounts of energy, with thermal efficiencies larger than a steady spray.

Introduction

In a spark-ignited engine with multi-point injection, the fuel evaporation is strongly dependant on the thermal-and fluid dynamics of spray impact onto valve and port surfaces, as well as on the local airflow conditions. In general fuel evaporation at the surfaces and, thus, fuel vapour concentrations are very transient in nature within the engine cycle and also within the time of injection. Improved knowledge of the transient energy flow is still required to devise strategies, not only to improve mixture preparation but also to deal with the large thermal stresses induced by the spatial and temporal temperature gradients at valve surfaces. Transients within the time of injection become particular important when the engine operates at high loads and low revolutions because more fuel impacts onto the surfaces and there is more time available for the temperature of solid surfaces to vary.

A research programme is being conducted aimed at characterizing the transient thermal-and fluid dynamic mechanisms of interaction of impinging gasoline spray. Previous work considered cold start conditions at which a transient liquid film forms at the surface, see Panão and Moreira [1], [2] and [3]. Recently, an experimental methodology has been devised (see Loureiro *et al.* [4]) to include the thermal effects, which combines droplet characteristics measured with a Phase Doppler anemometer and surface thermal behaviour measured with fast response thermocouples. The present paper considers further developments of that study and reports on the transient thermal interaction. Future work will include the development of correlations for heat transfer coefficients.

Experimental installation

The experimental set-up was designed to study a transient gasoline spray impinging onto a flat plate under cross-flow conditions, *e. g.* Panão and Moreira [2] although the results reported here consider quiescent surroundings. The spray is generated by a pintle-type injector with 0.79 mm of pintle diameter inserted in a cylindrical hole of 0.9 mm diameter. The spray has a hollow-cone structure with interior and exterior angle of 8º and 19º, respectively. A pressure regulation valve controls the injection pressure, while an NI5411 arbitrary function generator controls the frequency and the duration of injection. The pulse duration is selected as a percentage of the time between pulses (duty cycle), *e.g.* for a frequency of injection equal to 10 Hz each cycle has a period of 100 ms, therefore, a 5 ms pulse corresponds to 5% of the duty cycle.

The electromechanical delay was determined to be 1.6 and 1.3 ms for pintle opening and closing, respectively, and found to be independent of pressure and injection duration. Therefore, since the effective injection period is always 0.29 ms shorter than expected, the proper adjustment was made to the duty cycle percentage in order to match the desired pulse duration. The fluid used is a commercial gasoline with density of 758 kg/m^3, dynamic viscosity of 4.66×10^{-4} kg/m·s, refractive index of 1.44 and surface tension of 19.4 mN/m. The impinging plate, which is located at 55mm from the injector nozzle, is made of aluminium with a mean roughness of 0.76 µm and is 12 mm thick. Its thermal diffusivity (α_w) is 6.676×10^{-5} m^2/s and its thermal conductivity (k_w) is 164 W/m·K. The target is heated by an electric resistance isolated at the bottom. The temperature of the surface is measured by three NANMAC fast-response eroding-type thermocouples displaced in an L-shape. The junctions of the thermocouples are made by wearing the surface with an abrasive cloth until the thermocouple resistance is between 8 and 12Ω which insures a response time in the order of 10µs. A thermographic analysis showed that the thermocouples do not alter the uniform temperature distribution of the target. The thermocouple signals are amplified with a gain of 300 and digitized at a sample rate of 50 kHz. The system used to measure the wall temperature is schematically shown in Fig.1.

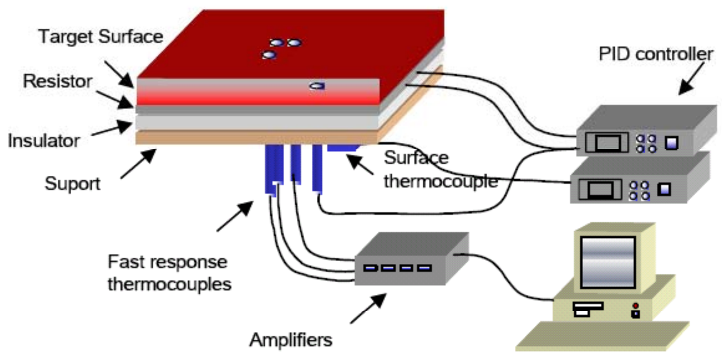


Figure 1 Temperature data acquisition system

A key issue to the present research is the measurement of instantaneous wall heat fluxes with high temporal resolution. Details of the method and assessments of accuracy are provided in Loureiro *et al* [4] and only a summary is given here. The method considers the one-dimensional transient energy equation (1) and the instantaneous heat flux given by Fourier's law (2), to derive an algorithm to estimate the instantaneous heat flux (3) from the temperature gradient at the impinging surface, provided that the boundary and initial conditions are obtained from time resolved measurements:

$$\begin{aligned} &\frac{\partial\theta}{\partial\tau}=\frac{\partial^2\theta}{\partial\xi^2},\\ &\tau=\frac{t\alpha_w}{h_w},\ \xi=\frac{z_w}{h_w},\ \theta=T_w-T_b \end{aligned} \tag{1}$$

$$\dot{q}''=-\frac{k_w}{h_w}\frac{\partial\theta}{\partial\xi}(0,\tau) \tag{2}$$

$$\begin{gathered} \dot{q}''(\tau_i)=2\frac{k_w}{h_w}\sqrt{\frac{\Delta\tau}{\pi}}\sum_{k=0}^{i-1}\left[\left(T'_{w,k}+T''_{w,k}\Delta\tau\left(i-\frac{2k+1}{2}\right)\right)\cdot R_{i,k}-T''_{w,k}\frac{\Delta\tau}{3}S_{i,k}\right],\\ \begin{cases} T'_{w,k}=\dfrac{T_{w,k+1}-T_{w,k}}{\Delta\tau}\\ T''_{w,k}=\dfrac{\left(T_{w,k+2}-T_{w,k+1}\right)-\left(T_{w,k}-T_{w,k-1}\right)}{2(\Delta\tau)^2}\\ R_{i,k}=(i-k)^{1/2}-(i-k-1)^{1/2}\\ S_{i,k}=(i-k)^{3/2}-(i-k-1)^{3/2} \end{cases} \end{gathered} \tag{3}$$

where t is a time instant, h_w and z_w are the length and the axial coordinate along the plate thickness, T_w is the temperature at the wall and T_b is the bottom surface temperature. T'_w and T''_w are the first and second order derivatives which were approximated with finite-differences. Boundary conditions consider the bottom surface of the plate at constant temperature and the initial conditions (t = 0 s) consider a uniform temperature distribution along the thickness of the plate.

Results and discussion

Heat transfer between the spray and the surface may follow different regimes, depending on the relative magnitude of the time scales associated with heat and mass diffusion, respectively. Those regimes are defined here based on the description of Naber and Farrell [6] for single droplets deposited onto a hot surface as depicted on the qualitative boiling curve of Figure 2. The curve exhibits a local maximum and a local minimum, correspond to the Critical Heat Flux (CHF) at the Nukiyama temperature, and to the Leidenfrost phenomenon, respectively. Four heat transfer regimes are identified:

Film Evaporation: $T_w \leq T_{sat}$;
Vaporization/Boiling: $T_{sat} \leq T_w \leq T_{Nukiyama}$;
Transition: $T_{Nukiyama} \leq T_w \leq T_{Leidenfrst}$;
Spheroidal Evaporation/ Leidenfrost: $T_w \geq T_{Leidenfrost}$.

In the film evaporation and boiling regimes, both considered as a *wetting regime*, a liquid film forms on the surface, despite in the latter bubbles may be formed by nucleation. In the *transition* regime, the liquid is in contact with the surface only intermittently, due to separations from the surface caused by vapour expelled from the liquid. Above the temperature for which a local minimum is observed in the boiling curve, occurs the Leidenfrost phenomenon, characterized by the appearance of a thin vapour layer, or vapour cushion, between the liquid and the surface, thus resulting in a *non-wetting regime*.

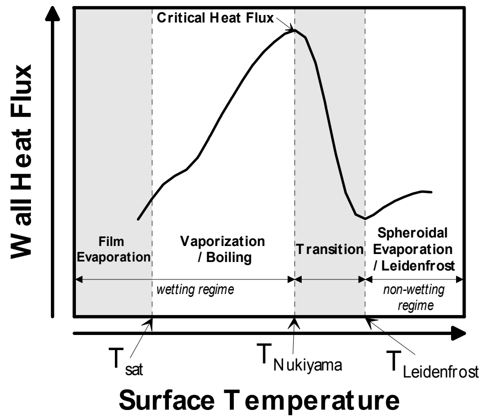


Figure 2 Typical boiling curve and definition of the heat transfer regimes

Heat transfer upon drop impact with the target surface is governed by flow and fluid thermal properties, as well as by surface roughness and temperature. However, heat transfer in poly-dispersed sprays may also be affected by the degree of interaction of multiple drops hitting the surface. As a consequence, surface temperature is not the single parameter determining different heat transfer regimes and other parameters associated with multiple drop impact interference, such as successive impact of some droplets on top of others, collision of droplet films during spreading and lamella interaction when the splash mechanism occurs, may have an important role in the impingement outcome, and also in the wall heat transfer. Therefore, the regimes defined above may vary within the area of impact. For a pulsed spray, which is simultaneously transient during injection due to pressure fluctuations associated with pintle opening and closing, those regimes will also vary in time in a way that depends on the time variation during each injection and on the degree of interaction between successive injections.

The effect of the frequency of injection on the thermal regimes of interaction is evaluated by injecting during 5 ms at frequencies between 10 Hz and 30 Hz, which simulates rotational speeds from 1200 rpm to 3600 rpm in a four-stroke engine. The time variation of surface temperature upon impact was recorded at the three thermocouples for series of 7 consecutive injections. Temperature measurements are then used as boundary conditions to equations (1)–(3) to calculate the temperature distribution across the target plate, from which the surface heat flux is estimated. The time-average heat flux removed from the surface is then obtained from numerical integration of the instantaneous heat flux:

$$\overline{\dot{q}''} = \frac{1}{T}\int_o^T \dot{q}''(t)dt \qquad (4)$$

where T is the time interval of integration. Since the temperature acquisition rate is high enough (50 kHz), the error in the time-average integration was less than 0.1% for the compose trapezes rule. A characteristic boiling curve can then be obtained for each injection frequency, by plotting the time-average heat flux against the initial surface temperature of the wall. The final result corresponds to a smooth of the seven curves obtained for each series of injections, as shown in Figure 3.

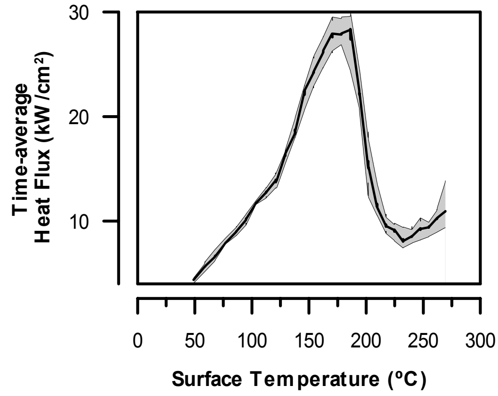


Figure 3 Example of the results obtained from smoothing the measured surface heat fluxes at 25 Hz to form average values. The shadow area corresponds to the bandwidth of scattered points.

Figure 4 depicts the boiling curves obtained in this way and confirms the influence of injection frequency on the thermal characteristics which define the regimes of surface heat transfer: the critical heat flux (CHF) at the Nukyiama surface temperature and the minimum heat flux (MHF) at the Leidenfrost temperature. Apparently, the CHF and MHF increase with the injection frequency, suggesting that the heat transfer is enhanced when the interaction between injections is promoted. Similar results were observed by Arcoumanis and Chang [7] with a high pressure Diesel spray striking a surface at a distance of 30 mm, when the frequency of injection was increased from 10 Hz to 20 Hz.

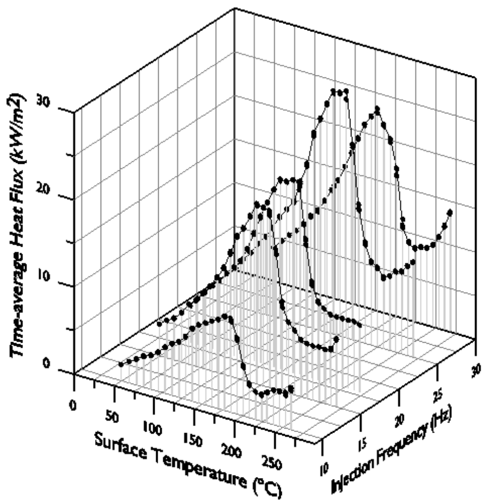
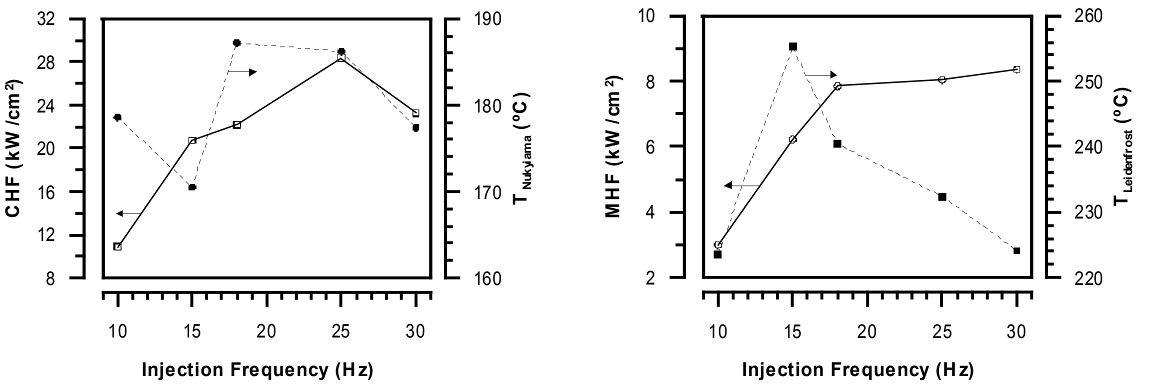


Figure 4 Variation of the time-average wall heat flux with surface temperature for injection frequencies of 10, 15, 18, 25 and 30 Hz.

A quantitative analysis can be inferred from the results in Figure 5: the Critical Heat Flux increases about 2.3 times when the frequency of injection increases from 10 Hz to 25 Hz and decreases thereafter; but the Nukyiama temperature does not show a definite trend and variations of its value are within 15ºC; the Minimum Heat Flux increases about 2.5 times up to about 18 Hz and remains constant thereafter, while the Leidenfrost temperature increases 20ºC up to 15 Hz and decreases thereafter, suggesting that a vapour cushion is easily formed as the interaction between injections increases.

Extrapolation of these results to a practical engine must be done with care, since heat transfer in the engine may also be affected by the air-flow through the intake port and by the hot combustion products on the backside of the intake valve. However, it is desirable that the Critical Heat Flux in a real engine remains constant at the steady state temperature of maximum thermodynamic efficiency, in order to keep the evaporation rate of the impacting fuel droplets high. Despite the unaccounted effects in our laboratory model, the results reported here suggest that the frequency of fuel injection also play a non-negligible role.



(a) (b)

Figure 5 Effect of the injection frequency on (a) the Critical Heat Flux and corresponding Nukyiama temperature; and on (b) the minimum heat flux and corresponding Leidenfrost temperature.

At this point it is worth comparing the results reported here with those observed in real engine operation. Cowart and Cheng [5] report measurements of surface temperature at the rear and at the front of the intake valves in a four-stroke engine with Port Fuel Injection. The authors found that the front surface of the valve is hotter than the rear and that temperature increases with engine speed at both locations. A qualitative picture is depicted in Figure 6, where the values reported by Cowart and Cheng [5] are plotted together with the Nukyiama and Leidenfrost temperatures measured in the present experiments. While the critical heat flux is available for fuel vaporization of the impacted fuel at the rear of the valve surface, in the front part, especially at higher engine speeds, part of the fuel may fell into the non-wetting regime and consequently less heat transfer is transferred to the impinging droplets.

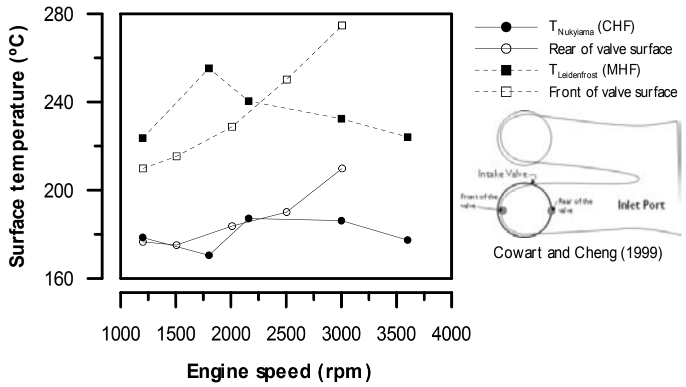


Figure 6 Comparison between reported intake valve temperatures with measured Nukyiama and Leidenfrost temperatures as function of engine speed

The analysis up to this point is inferred from measurements made at the central axis of the spray and suggests that the influence of high injection frequencies stems from the interaction between droplets injected at successive injections. But also the interaction of multiple droplet impact is expected to affect the heat transfer rate in a way that depends on the local number flux of impacting droplets. This effect is evaluated here based on heat flux measurements within the surface of impact.

Figure 7 depicts the boiling curves and the corresponding CHF and MHF measured at three radial locations within the hollow-cone structure of the spray, at which multiple droplet interaction is known to occur differently (*e. g.* [2]): r = 0 mm is a point within the hollow cone of the spray; r = 3 mm is located at the inner part of the conical sheet, where the number flux of droplets striking the surface is larger; and r = 6 mm, is at the outer edge of the spray. The results show that the highest CHF occurs where drop-drop interaction at impact is expected to be more intense, while the MHF decreases continuously from the centreline to the edge of the spray.

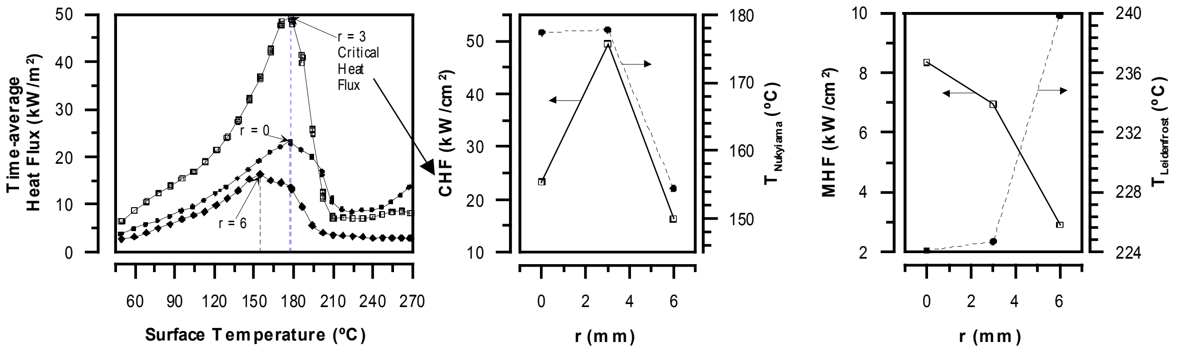


Figure 7 Radial variation of the Critical Heat Flux (at the corresponding Nukyiama temperature) and of the minimum heat flux (at the corresponding Leidenfrost temperature).

The analysis reported so far considers a gasoline spray operating at conditions similar to those found in spark-ignited engines. However, the results suggest that the interaction between successive injections and multiple droplet interaction may allow remove large amounts of heat from hot surfaces with thermal efficiencies larger than stationary sprays. More fundamental research is required to explore these characteristics to devise efficient spray cooling devices. To accomplish with that, an experimental methodology has been devised (see Loureiro *et al.* [4]) to perform simultaneous measurements of droplet characteristics (*e. g.,* 2D velocity, size and flux) and of surface thermal behaviour at impact. These measurements will consider other fluids and will allow a further insight into the heat transfer mechanisms at the impact of transient pulsed sprays.

Summary

This paper addresses the transient thermal interaction of a PFI injector spraying gasoline against a flat surface. Experiments were conducted to quantify the effects of operation conditions on the regimes of heat transfer. Characteristic thermal parameters of the thermodynamic system spray/target-surface, such as the Critical heat flux and the Leidenfrost temperature, were found to depend on the frequency and duration of injection as well as on the pressure of injection. The results reported here emphasize the effects of injection frequency: *i)* the Critical Heat Flux increases about 2.3 times when the frequency of injection increases from 10 Hz to 25 Hz and decreases thereafter; *ii)* the Minimum Heat Flux increases about 2.5 times up to about 18 Hz and remains constant thereafter; *iii)* the Nukyiama temperature does not show a definite trend and variations of its value are within 15ºC; *iv)* the Leidenfrost temperature increases 20ºC up to 15 Hz and decreases thereafter. The results further show non-negligible variations within the surface of spray impact, which are attributed to the effects of multiple droplet interaction.

The present results were compared with measurements made in a real engine and reported in the literature for a range of rotational speeds. It is shown that the Nukyiama temperature at which the heat removed is maximum is close to the temperature at the front of the valve where the fuel spray impacts directly; while the Leidenfrost temperature at which the heat removed is minimum is close to the temperature at the rear of the valve.

An experimental methodology was recently devised by the authors and is currently in use to correlate the instantaneous thermal behaviour of the surface with droplet characteristics at impact (size, 2D velocity and flux). The analysis will then be extended to other fluids in order to explore the transient characteristics of pulsed sprays to enhance the performance of spray cooling devices.

Acknowledgements

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