Drop impact on a heated wall – influence of ambient pressure

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This paper reports on experimental investigations of the normal impact of ethanol and iso-octane monodisperse drops on a solid heated surface under different temperature and pressure conditions. The aim of this work is first to characterise the various impact regimes under atmospheric pressure; two main regimes have been encountered, i.e. liquid deposition and splashing. The second step consists in quantifying the influence of ambient pressure on these regimes and on the size of secondary droplets, in the splashing regime.

1. Introduction

For a few years, the research about internal combustion engines has been focused on the clean combustion, in order to reduce exhaust emissions and to improve the fuel consumption. A direct injection type for gasoline engine has been considered to solve these problems. The reduction of the quantity of unburned droplets in new Direct Injection gasoline engines is closely linked to an increase of the understanding of fuel drop behaviour. The modelling of each physical phenomena occurring into the combustion chamber is required to improve the level of prediction of the numerical codes. Due to the complexity of a dense spray, elementary phenomena are studied from basic experiments using monosized droplets. This survey is dedicated to drop-wall interactions, a subject that has been studied for more than one century [1] but which is still a topical issue. Therefore, many studies have been carried out at atmospheric pressure to evaluate the influence of the main characteristics parameters of the droplets (size and velocity [2,3], impact angle [3,4], liquid properties such as viscosity and surface tension [2], Weber number [5]) and the properties of the wall (roughness [2] and temperature [3,6,7]) on the impact configuration. But almost no work deals with the influence of ambient pressure on the drops behaviour. The aim of this investigation is to identify the different droplet regimes and to provide information about the effects of the ambient pressure on the boundaries of these regimes, at different surface temperatures, by using the shadowgraphy technique, a CCD camera and an appropriated image processing.

2. Experimental set-up

The experimental set-up is made up of a high-pressure test-rig working up to 80 bar. The simplified injection system is located inside the pressure vessel and connected to a small pressurised tank containing the working liquid. Monodisperse drops are thus generated (based on the Rayleigh instabilities principle) with a diameter close to 100 µm. Two different liquids are used: ethanol C_2H_6O and iso-octane C_8H_{18} (the thermodynamical properties are given in tab.1 below). The generated jet impinges with a 90° angle on an aluminium alloy sample of a piston bowl (with a 5.8 µm roughness), which is electrically heated from below by a cartridge and regulated by a PID system. The temperature of the wall is thus controlled by a thermocouple located under the surface and at the centre of the piston.

	ρ (kg.m^{-3})	**σ (N.m^{-1})**	**µ (Ns.m^{-2})**	**T_{Leid} (K)**	**T_{sat} (K)**	**T_{crit} (K)**	**P_{crit} (bar)**
Ethanol	779,8	0,022	0,001016	458	351,5	516,3	63,8
Iso-octane	688,8	0,0182	0,000466	457	372,4	543,8	25,7

Tab. 1: Thermophysical properties of ethanol and iso-octane

The optical apparatus is composed of a CCD camera (CV-M10 BX, 768x576 pixels) coupled with a stroboscopic lamp. Each short flash of the lamp (0.1 µs) is synchronised with the camera exposure time to freeze the images of the droplets on the monitor of the computer. An image analysis software is also used to develop home built routines in order to measure the droplets size, velocity, shape, etc… The characteristics of the camera allow the measurement of drops size ranging from 6 to more than 500 µm diameter (1 pixel corresponds approximately to 2 µm in the granulometry configuration – zoom view – and 7 µm for the visualisation of impact regimes – standard view).

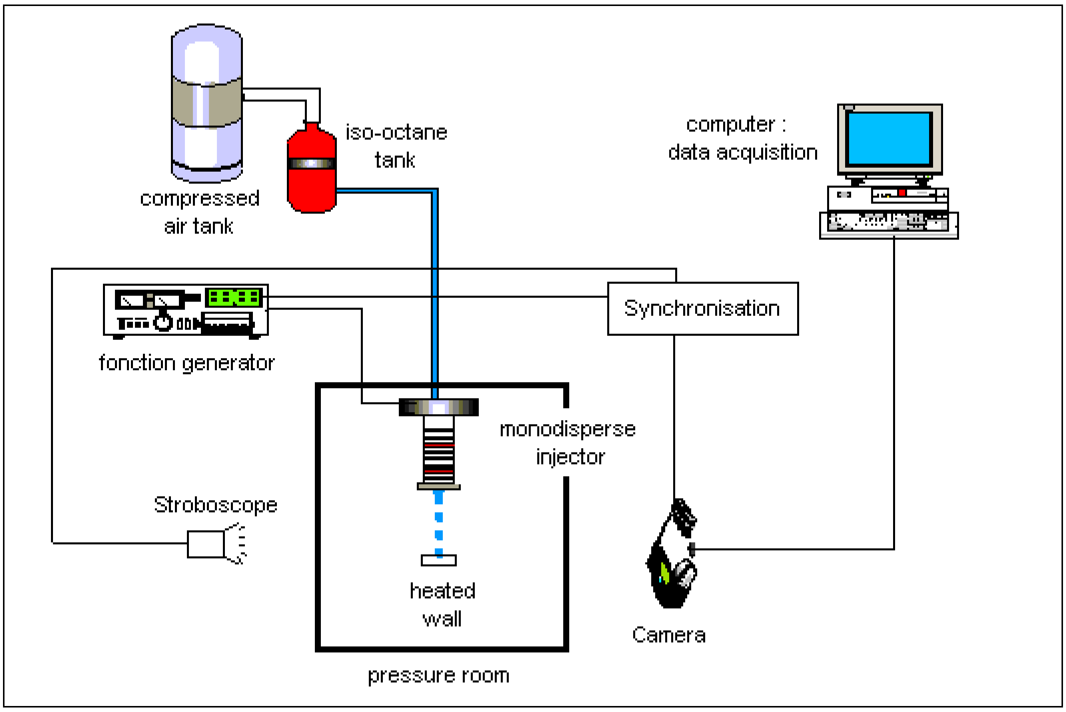


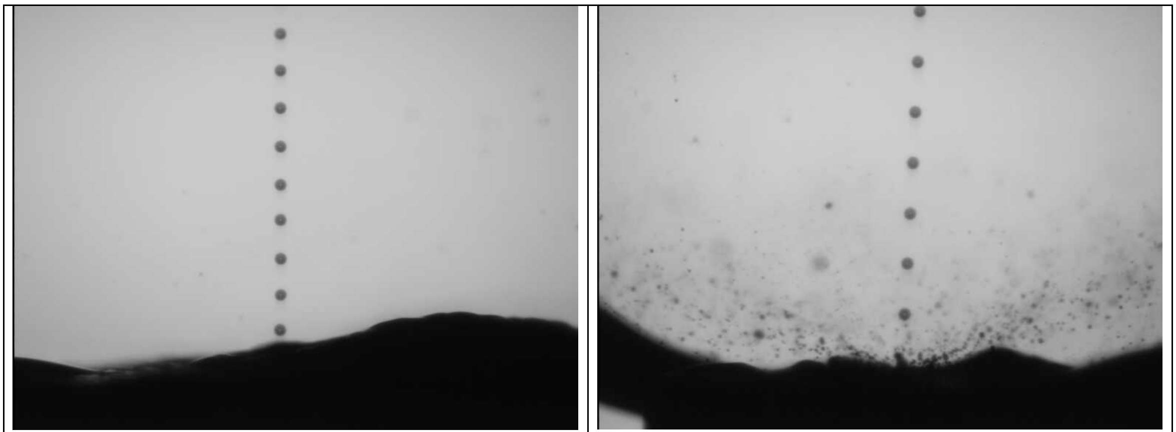
Fig. 1: Experimental set-up

3. Results and discussion

The main goal of this work is to understand the effects of the ambient high pressure on the impact configuration and on the secondary droplets break-up regimes. Firstly, the impact regimes have been characterised under atmospheric pressure, and then in a pressurised environment. Secondly, the consequence of a variation of the ambient pressure on the granulometry of secondary droplets has been evaluated.

3.1. Regimes observed under atmospheric pressure

Experiments have been carried out with two liquids (iso-octane and ethanol). The generated drops have an incident diameter (D_0) of 100 µm and an impinging normal mean velocity (V_0) ranging from 3 to about 8 m/s, so that the incident Weber numbers (We) are ranged between 150 and 350. For the prescribed wall temperatures (approximately from 360 K up to 500 K), only two main regimes are observed: the liquid film for low temperatures, the splashing regime for higher temperatures (fig. 2). We can still distinguish two types of splashing, the bubble boiling and the film boiling. Indeed, for low wall temperatures (below the boiling point of the liquid used) incident drops impinge and merge themselves on the wall, therefore generating a liquid film. When the wall is heated up close to the boiling point temperature, small bubbles appear inside the liquid film and also generate small secondary droplets (bubble boiling). Finally for temperature values above the Leidenfrost point, the disintegration process is piloted by the Leidenfrost phenomenon: it looks as if the whole liquid film were on levitation above the heated wall. Bigger secondary droplets are thus generated. This phenomenon is well known and also called the spheroidal state [8].



-a- -b-

Fig. 2: Impact regimes under atmospheric pressure, iso-octane, D_0=100 µm (a- Liquid film T_w=108 °C, b- Splashing T_w=189 °C)

3.2. Influence of pressure on impact regimes

To evaluate the effect of the ambient pressure on the regimes previously defined under atmospheric conditions, the impinging jet has been settled under pressure values ranging from 1 to 8 bar. Except the pressure, no other parameter has been modified in comparison to the experiments conducted at atmospheric pressure (incident drop size and velocity, impact angle, ambient temperature, wall material and roughness). For each case, the wall temperature is increased step by step to determine the limit between liquid film and splashing regimes. Then, these results are collected in a chart giving the temperature of the wall over the pressure and compared with the curve representing the evolution of the boiling point temperature of the liquid with the ambient pressure. Several equations already exist in the literature, the correlation of Frost-Kalkwarf-Thodos [9] was chosen because the pressure range of our experiments corresponds to the validity interval, it is defined as follows (1):

$$\ln P_{vp} = A + \frac{B}{T} + C.\ln T + \frac{D.P_{vp}}{T^2}$$

where A, B, C and D are constants depending on the liquid used

Figure 3 shows the results obtained for iso-octane drops and figure 4 for ethanol droplets. The general trends and comments between the two liquids are quite similar.

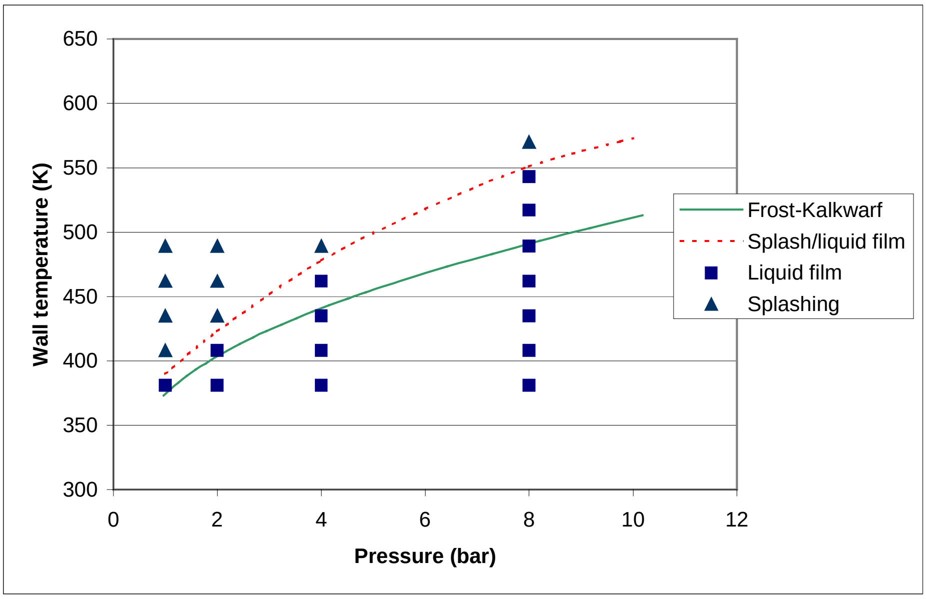


Fig. 3: Impact regimes for several pressure and temperature conditions (iso-octane drops)

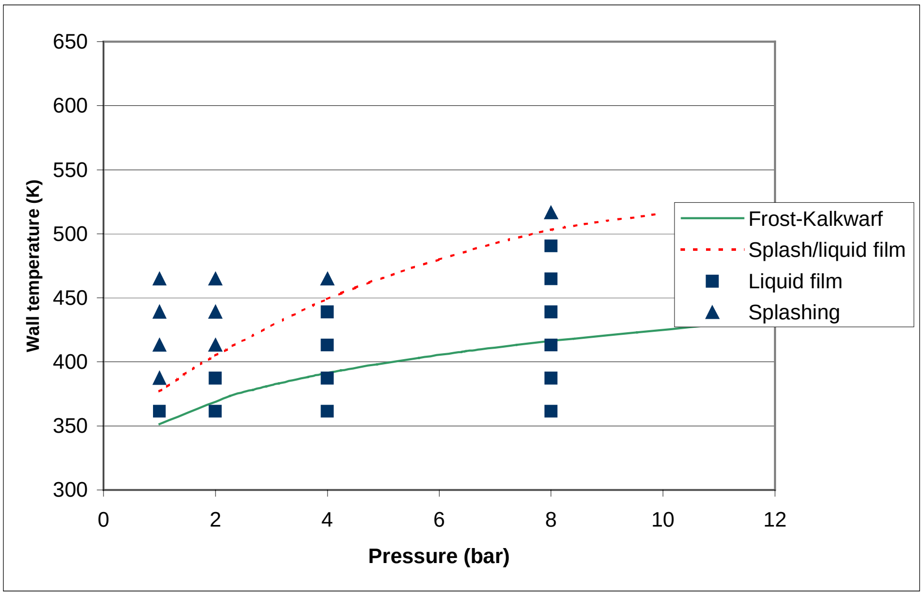


Fig. 4: Impact regimes for several pressure and temperature conditions (ethanol drops)

The full line is the estimated iso-octane boiling point temperature according to the Frost-Kalkwarf-Thodos equation, the small triangles and squares are experimental data and the dashed line represents the experimental limit between liquid film and splashing. We can first notice that, for low pressure values, the splashing regime occurs at small wall temperatures. Indeed, the limit between the two impact regimes (liquid film and splashing) moves up to higher wall temperatures when the ambient pressure increases. This can be explained by the fact that the boiling temperature of a liquid increases with the ambient pressure (1). The evolution of the splash/liquid film limit is quite similar to the boiling point temperature curve, at least for small pressure values. This phenomenon reveals that the boiling temperature of a liquid has a large influence on impact regimes, but it is not the only parameter. One reason for which the gap between the splash/liquid film limit and the Frost-Kalkwarf-Thodos correlation increases for high pressure values could be due to the fact that the velocity of impinging drops decreases when the ambient pressure increases. Initially droplets are injected with the same velocity; due to air density which increases with pressure, the drag forces also increase and as a consequence droplets are slowed. This phenomenon has been focused by C. AMIEL [5], for who a decrease of the incident Weber number (or incident velocity) favours the deposition regime.

3.3. Influence of pressure on secondary droplets

The final step of this work concerns the drop measurement of secondary droplets in the splashing regime. For each value of the pressure, at least 1000 droplets are considered so that the sample is representative to perform with confidence a statistical treatment of the data. The droplets are classified by the size and their number is also quantified in each class of diameter (see fig. 5). Experiments have been carried out with iso-octane incident drops of 100 µm. The pressure values were ranging from 1 to 4 bar and a constant wall temperature of 489 K (corresponding to T_w/T_{crit}=0.9) was chosen so that the splashing regimes occurred for the three cases.

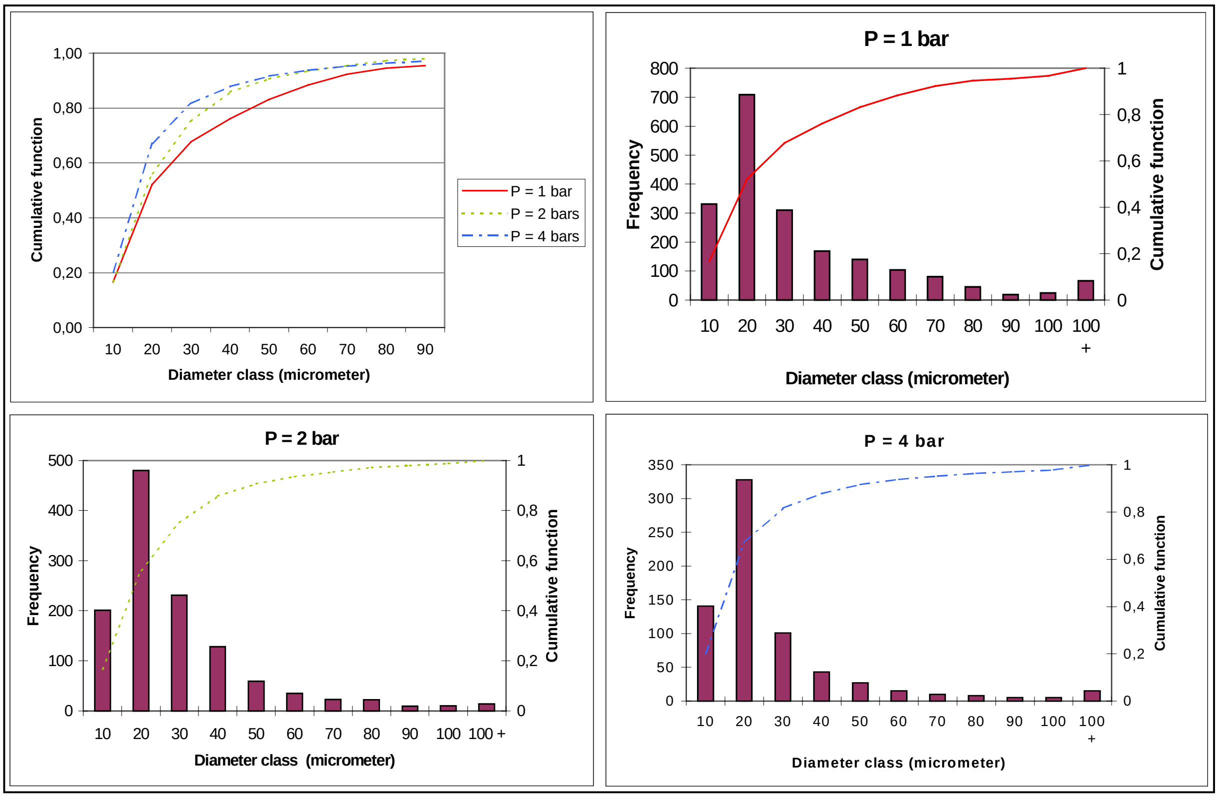


Fig. 5: Influence of ambient pressure on secondary droplets

To make some comparisons between the data obtained for each value of the ambient pressure, one significant diameter is used, the Sauter Mean Diameter D_{32}, defined as follows (2):

$$D_{32} = \frac{\sum n_i . d_i^3}{\sum n_i . d_i^2}$$

where n_i is the number of drops belonging to the class of diameter d_i

The influence of ambient pressure on the D_{32} is given in table 2 below:

P_{amb} (bar)	D_{32} (µm)
1	84
2	67
4	54

Tab. 2: Influence of ambient pressure on D_{32}

The D_{32} values are lower for P_{amb} = 2 bar than at the atmospheric pressure and this tendency is also confirmed by the case P_{amb} = 4 bar, for which the droplets after impingement are still smaller. Figure 6 below shows drop-wall heat transfer regimes and is useful for explaining the experimental observations:

- for 1 and 2 bar conditions, the wall temperature (489 K) is above the Leidenfrost temperature, so the impaction regime is driven by the Leidenfrost phenomenon and big secondary droplets coming from the film boiling are also generated.
- on the other hand, for Pamb = 4 bar the generation of secondary droplets comes from the boiling of small bubbles contained in the liquid film (bubble boiling regime). This is due to the fact that the Leidenfrost temperature increases with the pressure [10] and for 4 bar, the wall temperature should be under the Leidenfrost temperature.

To sum up, the splashing regimes observed for those two cases are not exactly the same (film boiling and bubble boiling) and this accounts for the evolution of the secondary droplets size (smaller for high pressure values).

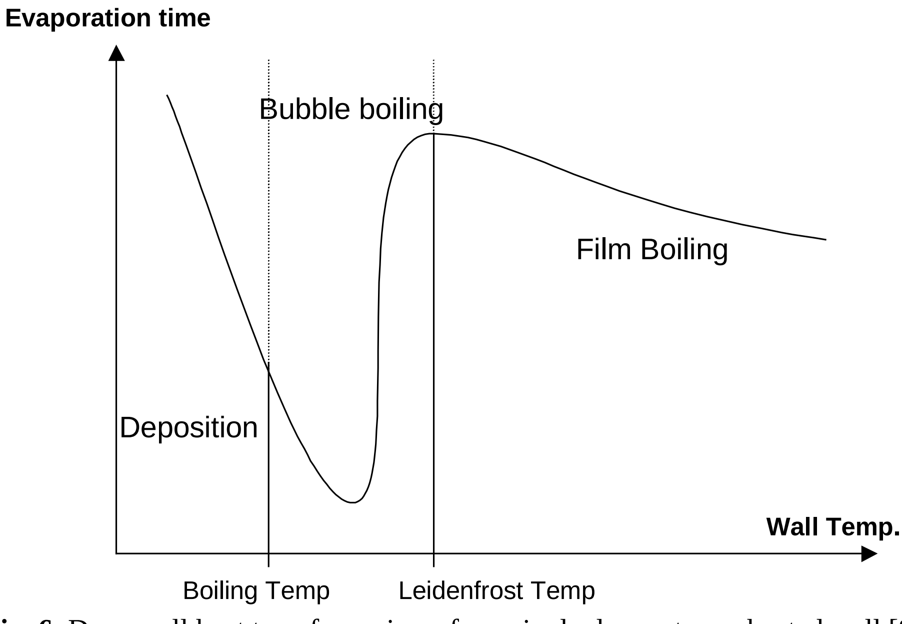


Fig. 6: Drop-wall heat transfer regimes for a single drop set on a heated wall [8]

4. Perspectives

The experiments conducted in this survey have been carried out only for a normal impact of the incident jet. It would be of great interest to test different impact angles (e.g. from 10 to 90°), in order to experiment every impact configuration that can be encountered inside a GDI combustion chamber.

5. Conclusion

The impinging behaviour of a monodisperse jet under several pressure conditions has been experimentally investigated to determine general tendencies. Two liquids (iso-octane and ethanol) with physical properties close to gasoline ones have been used and a consequent range of wall temperatures was tested.

- The results have shown that two main regimes have been encountered for the operating pressure and wall temperature conditions: liquid film for low pressure and temperature values, splashing for higher ones.
- Moreover, an increase of the ambient pressure inside the test-rig favours the liquid film regime because of an increase of the boiling point temperature of the liquid.
- The size of the generated secondary droplets decreases when the pressure values increase, due to a change of the phenomenon driving the splashing regime.

6. Nomenclature

D_0	diameter of an incident drop [μm]
D_{32}	Sauter mean diameter, $D_{32}=\Sigma\, n_i.d_i^3 / \Sigma\, n_i.d_i^2$ [μm]
P_{amb}	ambient pressure [bar]
P_{crit}	critical pressure [bar]
P_{vp}	vapour pressure [bar]
T_{crit}	critical temperature [K]
T_{Leid}	Leidenfrost temperature [K]
T_{sat}	saturation temperature [K]
T_w	temperature of the wall [K]
V_0	normal velocity of an incident drop [$m.s^{-1}$]
We	Weber number, $We = \rho.V_o^2.D_o/\sigma$
μ	liquid dynamic viscosity [$Ns.m^{-2}$]
ρ	liquid density [$kg.m^{-3}$]
σ	surface tension [$N.m^{-1}$]

7. Acknowledgements

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8. References

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