EXPERIMENTAL STUDY OF A CR DIESEL SPRAY (ILASS 2002)

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Abstract
An experimental study of diesel sprays from a Common Rail (CR) injection system has been performed. Spray evolution and its impact on a flat wall have been visualized and the main parameters analyzed varying the injection pressure, the backpressure of the gas in an optically accessible test chamber and the temperature and the slope of the flat wall.
The spray has been lightened by a pulsed laser sheet generated by the second harmonic of a Nd-YAG laser. The scattered light has been collected at right angle with respect to the laser sheet by a CCD camera which frame grabber has been synchronized with the single-shot injection command and the laser start pulse.
A digital image processing software has allowed to extract characteristics parameters of the spray and of the evolution of the fuel on the wall after the impact.
Shape, structure, temporal and spatial evolution of the spray have been measured and the results have provided useful information for a better understanding of the high-pressure sprays phenomena produced by common rail injection systems.

Introduction

Modern high pressure electronically controlled Common Rail injection systems are successfully used in diesel engines, allowing to shape the injection curve, to reduce emissions, to get a better fuel economy and to provide more comfort. Due to the high injection pressure used, the velocities of the droplets emerging from the nozzle assume values grater than 300 m/s and strongly atomise. In small size engines, a large amount of fuel reaches the wall of the combustion chamber before vaporize, so the spray structure and the wall-impingement assume a relevant role in the short time available to prepare the mixture ready to be burned before the start of ignition[1-5].

Jet impingement on a flat wall expands the total volume occupied by the fuel, producing a lot of new droplets and increasing the gas entrainment in the spray [6-8]. It behaves in a significantly different way depending on the injection pressure, the backpressure in the chamber and the wall temperature [5-7] and [9].

An experimental study of a diesel spray emerging from a CR apparatus has been carried out. The characteristics of the free evolving spray and of its impact on a flat wall have been studied varying the injection pressure (80 - 120 MPa), the backpressure (0.1 – 5.0 MPa), the temperature of the flat wall (296 - 773 K) and its slope. The last has been defined as the angle between the spray axis and the normal to the surface and has varied between 0° and 30°.

Results provide useful information for a better understanding of the phenomena related to the high-pressure sprays produced by common rail injection systems.

Experimental apparatus

The experimental apparatus, shown in fig. 1, consists of a constant volume spray chamber, a high pressure fuel injection system, a heated stainless steel flat plate, an imaging system and a data acquisition and control system. The flat plate has been positioned on a X-Y-Θ goniometric system for its angular regulation.

The sprays have been generated, in single-shot mode, by an electronically controlled Common Rail (CR) injection system. Open software, via an Electronic Control Unit (ECU), has allowed setting the injection pressure, the injection duration and the timing. An injection duration of 1.0 ms and injection pressures of 80 and 120 MPa have been set with delivered fuel quantities of 8.44 10^{-3} g/shot and 9.67 10^{-3} g/shot, respectively. The ISO 4113 calibration fluid has been used as standard diesel fuel. An axial single-hole mini-sac nozzle injector type has been used with the hole diameter and length of 0.18 and 1.0 mm, respectively.

The sprays, emerging co-axially with respect to the chamber, have been lightened, at different time from the SOI, by a pulsed laser sheet, 80 μm thickness and 12 ns duration, generated by a Nd-YAG laser operating on its

second harmonic. The images have been captured by a PULNIX TMC-6 CCD camera, synchronized with the laser pulse, providing images size of 768 x 568 pixels with 8 bits intensity resolution.

Spray structure and morphology, jet cone angles, tip penetrations and impact geometry have been obtained by suitable software developed to process the acquired images.

Further details about experimental apparatus and image processing procedures have been reported in [10-12].

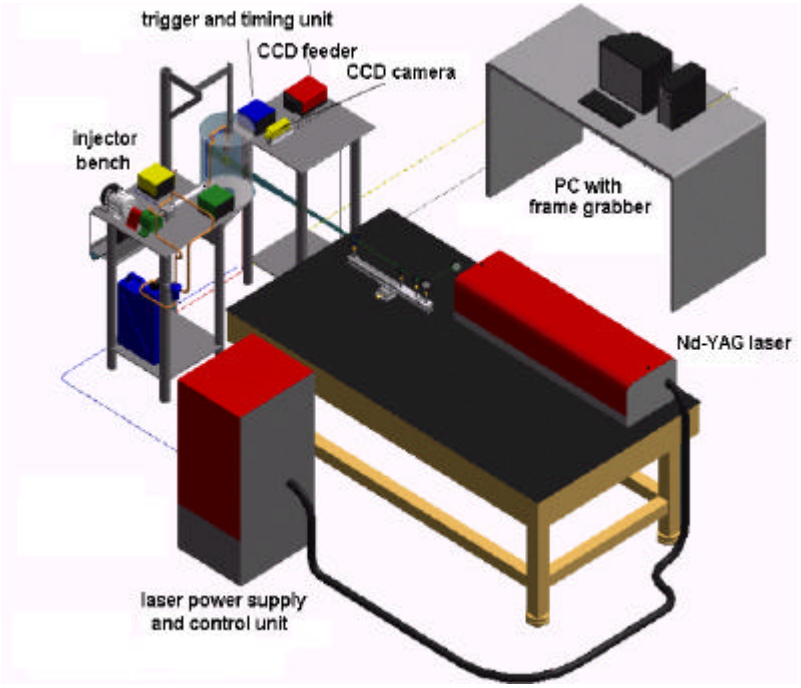


Fig. 1. Experimental apparatus

Results and discussions

Fig. 2 shows free spray evolutions at the operating conditions P_{inj} = 120 MPa, t_{inj} = 1.0 ms and backpressures P_{amb} of 0.1, 3.0 and 5.0 MPa, respectively.

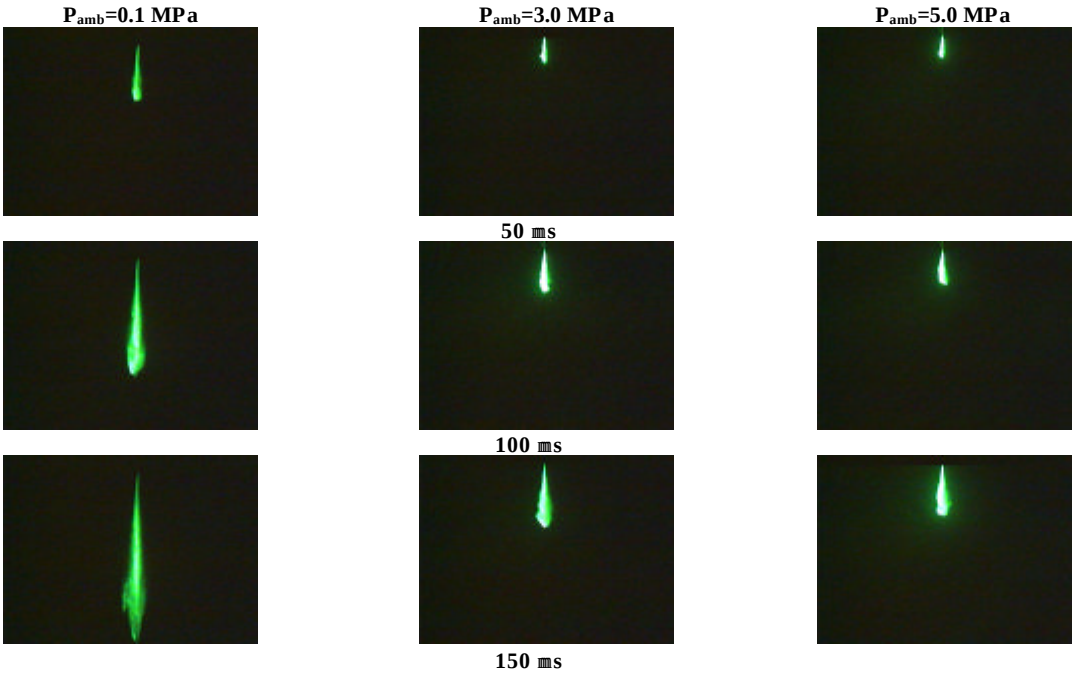


Fig. 2. Free spray evolution; P_{inj}=120 MPa, t_{inj}=1.0 ms

Sprays are characterized by high values of momentum and strongly penetrate the ambient gas at backpressure of 0.1 MPa, with constant spray tip velocities of about 300 m/s up to about 50 mm from the injector tip.

The pressure of the gas in the test chamber strongly affects the spray tip penetrations. Increasing the backpressures, spray tip penetrations and velocities reduce.

The pseudo-colour conversion and binary transformation techniques [10] have been applied to the collected images to extract the shape and the section structure across the axial plane of the spray. The techniques allow to determine characteristic parameters of the phenomenon such as the spray cone angle, the leading edge penetration and velocity.

In fig. 3 the conversion in pseudo-color image of the fully developed diesel spray, at the operating conditions: P_{inj} = 120 MPa, P_{amb} = 0.1 MPa, t_{inj} = 1.0 ms, is reported, showing the structure and shape of a free evolving jet. The spray consists of a "main jet region" and a "mixing flow region".

The first region lies in the inside of the spray, is characterized by high values of the fuel density and it's rounded by finely atomised droplets stripped in interaction with the gas in the chamber forming the "mixing flow region". After the characteristic initial length, ripples appear on the spray boundary due to its growth and interaction with the surrounding air flow characterized by reverse direction.

In small DI engines, the distance between the wall and the nozzle tip is not far enough for fully developing of the spray as shown in fig. 3. To characterize the spray evolution in such engines, an investigation on the impinging diesel spray in not developed main jet and mixing flow regions is necessary.

Fig. 4 shows pseudo-colour image of a typically picture of the spray, impinging perpendicularly to the plate, at enough time from the SOI to consider the impact completely developed. The operating conditions are: P_{inj} = 120 MPa, P_{amb} = 0.1 MPa, t_{inj} = 1.0 ms.

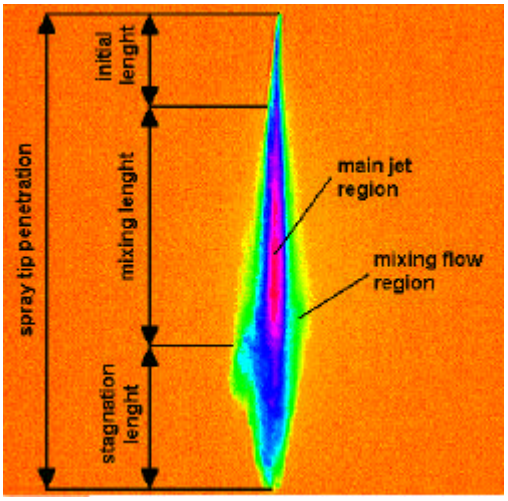


Fig. 3. Structure and shape of a free evolving spray

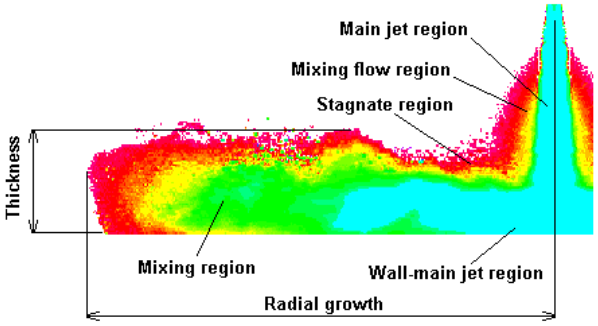


Fig. 4. Structure and shape of an impinging spray

In the figure the left half of the spray has been reported, being the fuel evolution on the wall axial-symmetric after the impact. Different spray regions appear in the image analysis. Higher density values of the particles in the impact zone are evident.

This constitutes the "wall-main jet" region with density values comparable to "main jet" region of free running spray. Far from the impact point, a "mixing" region is identified where relatively large droplets interact with the gas and curls and vortexes appear.

Finally, a "stagnate" region in the interface between the incoming primary spray and the outward traveling fuel is recognized. Here the layer thickness is sensibly lower meaning an upper limit to the rebounding angle from the plate, characterized by low density and size of the droplets.

Characteristic parameters of the impinging spray are considered the radial growth and the thickness, shown in fig. 4.

The radial growth, indicates the maximum distance reached by the fuel with respect to the spray axis, while the thickness is the maximum height of the rebounded droplet after the impact. Both them are a function of the time from the SOI. Particularly the thickness is assumed as a measure of the droplets lifetime after the impact on a heated plate. Its value is the average position of rebounding and vaporizing droplets.

The effects on the radial growth and thickness of injection pressure, backpressure, distance and slope of the wall are reported.

The figures 5 and 6 show the spray thickness and radial growth, respectively, versus the time from SOI, for two injection pressures (80 MPa, and 120 MPa), being backpressure 0.1 MPa and the wall positioned at right angle with respect to the spray axis.

Increasing injection pressure the radial and the thickness growth of the impinging spray become faster, this trend being more evident for the thickness. Consequently, the low droplets density regions increase, resulting the gas-fuel mixing process promoted by higher values of the injection pressure.

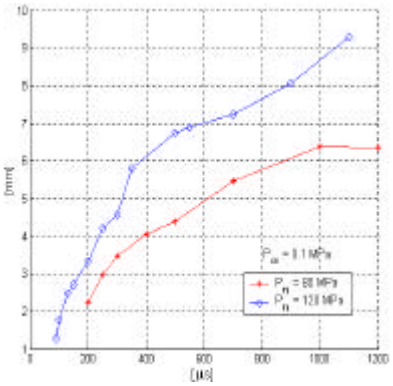


Fig. 5. Spray thickness versus time from SOI for different injection pressures

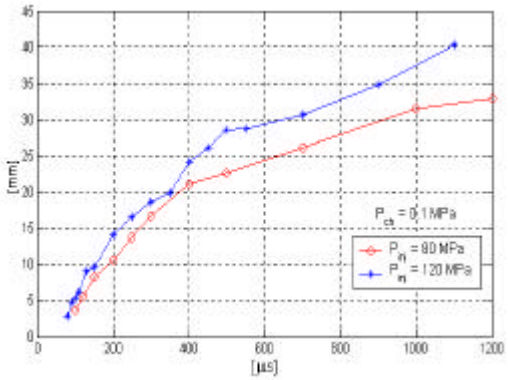


Fig. 6. Spray radial growth versus time from SOI for different injection pressures

The fig. 7 and 8 show the radial and thickness growth of the spray versus the time from SOI at four different backpressures in the vessel (0.1, 1.0, 3.0 and 5.0 MPa), respectively.

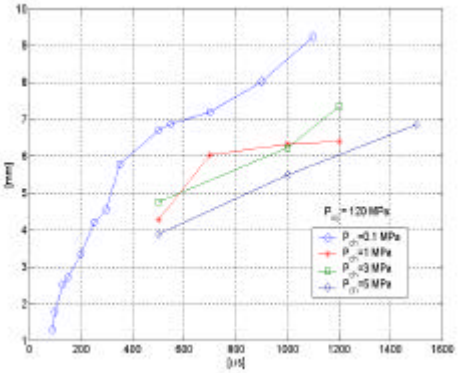


Fig. 7. Spray radial growth versus the time from the SOI for different backpressure; injection pressure 120 MPa

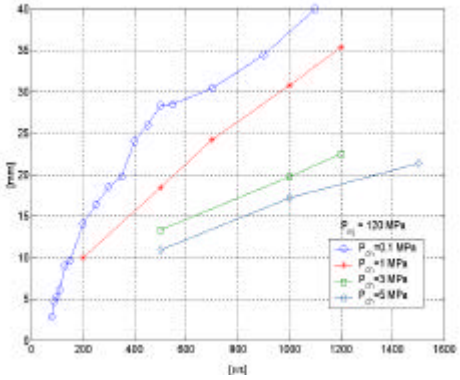


Fig. 8. Spray thickness versus the time from the SOI for different backpressure; injection pressure 120 MPa

Increasing the backpressure, the radial penetration of the spray slows down due to the increase of the resistance of the gas in the chamber. This trend is similar to the gas density effect on the tip penetration of the free diesel spray.

The spray thickness has a remarkable contraction when the backpressure increases. Fig. 9 shows the impinging spray profiles at the three times after SOI 0.2, 0.5 and 1.0 ms and at the two injection pressures of 80 and 120 MPa, being the wall temperature, T_w , 23, 200 and 500 °C, respectively. The backpressure was 0.1 MPa and the spray evolved in non-evaporative conditions.

The spray thickness has a trend similar to the lifetime of a liquid droplet impinging on a hot plate [13, 14]. As the wall temperature T_w increases from T_{amb} to 200 °C, the thickness slightly decreases. Then it increases for T_w equal to 500 °C. The effect is more evident at longer time from the SOI (1.0 ms). This trend contrasts the idea that the upper side of the fuel layer, that is the measure of the thickness, is principally constituted by droplets that undergo strongly the temperature effect and should vaporize. Really, the large size droplets inside this region, at higher values of T_w, rebound on the wall due to the Leidenfrost phenomenon [14]. These effects are more evident at p_{inj} of 120 MPa.

This trend is similar to the results reported in [5] for the impingement on hot wall of a spray emerging from a single hole injector supplied by a conventional PE-Bosch injection pump and it classify the dynamic and heat transfer processes in the three regions of wetting, transition and non-wetting [5], [14].

Figure 10 shows the time evolution of the impinging spray on the flat wall located at 22 mm from the injector with the axis inclined of 30° respect the spray one, at the operating conditions of: P_{inj}=120 MPa, P_{amb}=0.1 MPa, t_{inj}=1.0 ms.

Respect to the normal impact producing an axial symmetric evolution of the spray, in the sloped configuration almost all the fuel mass is shifted on a half plate. In the 30° impingement the radial growth reaches values greater than the horizontal one with a sensibly steeper rate while the thickness shows quite similar values.

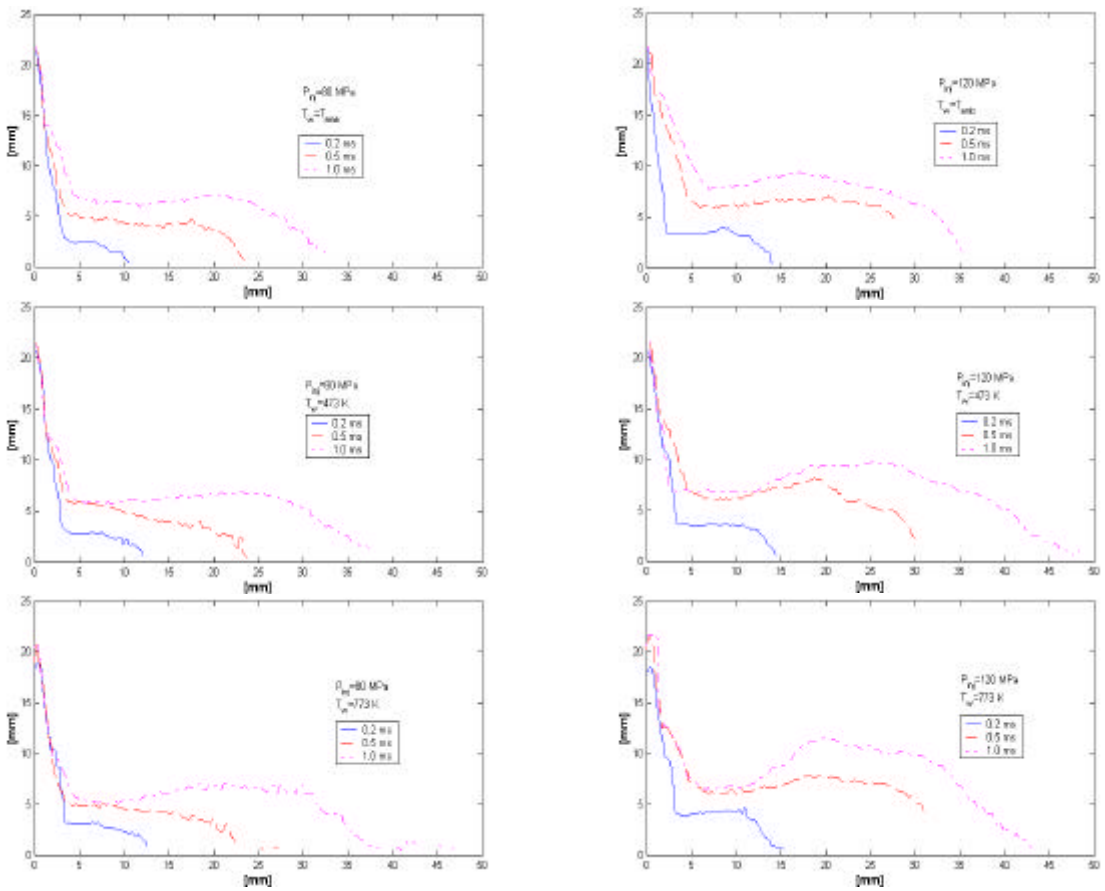
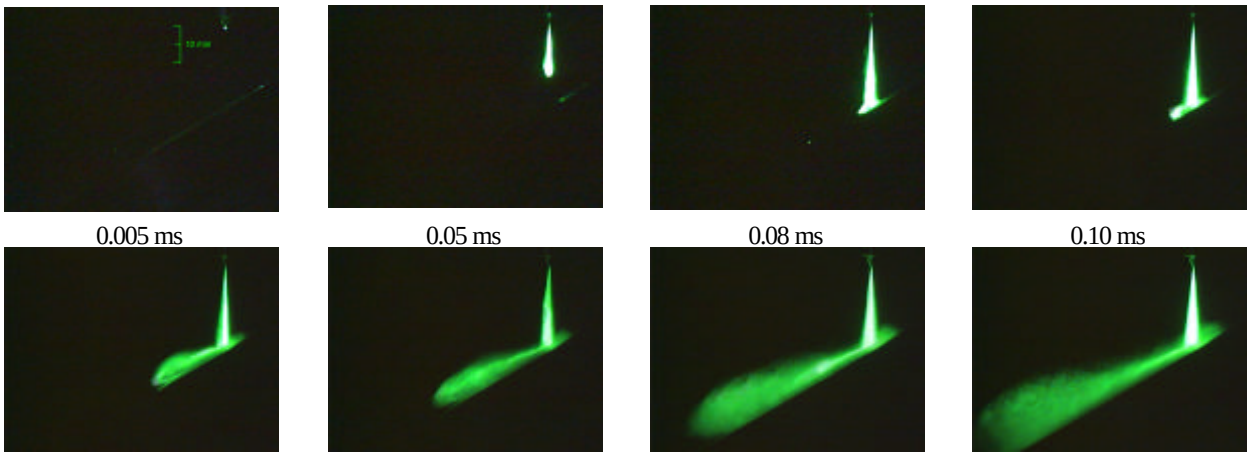


Fig. 9. Profiles of the spray after impingement at different time from the SOI, three wall temperatures, and two injection pressures



0.005 ms 0.05 ms 0.08 ms 0.10 ms

0.20 ms 0.30 ms 0.50 ms 0.70 ms

Fig. 13. Spray time evolution of the impinging spray; P_{inj}=120 MPa, P_{amb}=0.1 MPa, t_{inj}=1.0 ms, T_w=296 K.

Conclusion

A non-evaporative fuel was injected into a high-pressure test chamber, at room temperature and quiescent gaseous environment from a common-rail injection system for diesel engines.

The shape, the structure and the temporal and spatial evolution of the impinging spray have been measured by processing techniques of the collected spray images. The emerging liquid from the nozzle has been lightned by a pulsed laser sheet from a Nd-YAG at 532 nm (80 μm thickness and 12 μs duration) and acquired by a CCD camera, at different time from the SOI and different operating conditions.

The results may be summarized as follows:

1. the experimental set up and the used image processing technique have enabled to obtained detailed information on the shape and the structure of the impinging spray, allowing to visualize the spray

characteristic regions: “main jet”, “mixing flow”, “wall-main jet”, “stagnate” and “peripheral edge”. The experimental procedures also allow a quantitative description of the impinging spray, in terms of spray cone angle, leading edge penetration and velocity, axial and radial growth of the spray on the wall.

2. At increasing injection pressure the radial growth and the thickness of the impinging spray become faster, being this trend more evident for the thickness. Consequently, the low droplets density regions increase, resulting the gas-fuel mixing process promoted by higher values of the injection pressure.
3. Increasing the backpressure the radial penetration of the spray slows down and the mixing flow region and the low density upper side of the spray are undeveloped. At higher values of the gas in the test chamber, the volume of the impinging spray decreases, and the region of low droplets density, the region of the better air/fuel mixing, decreases.
4. Varying the temperature of the impinging wall, the thickness of the fuel layer has a trend similar to the lifetime of liquid droplets on a hot plate. It qualitatively classifies the dynamic of the heat transfer process in the three regions of wetting, transition and non-wetting.
5. In the sloped impingement, greatest part of the fuel is located on a half part of the plate and the radial growth reaches values greater than normal impingement one with a sensibly steeper rate.

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