ILASS 2008
Sep. 8-10, 2008, Como Lake, Italy

Paper ID ILASS08-13-1

POLYGONAL SPLASHING PATTERNS IN DIESEL JET IMPINGEMENT ON A SOLID WALL

M. Weclas and J. Cypris

Georg Simon Ohm University of Applied Sciences Nuremberg
Georg-Simon-Ohm-Hochschule Nürnberg, Fakultät Maschinenbau
Institut für Fahrzeugtechnik (IFZN)
Kesslerplatz 12, D-90489 Nürnberg
Email: miroslaw.weclas@ohm-hochschule.de

ABSTRACT

Under certain conditions Diesel jet wall impingement results in triangular (polygonal) splashing shapes. This process has been found to be almost independent of injection pressure, injection frequency or of the injection duration. The triangular splashing shapes are observed at a given transition time after Diesel jet wall contact. This time depends on the distance from the wall and on the injection pressure (jet velocity). This triangular splashing process is dependent on the distance from the wall, and does not correspond to a typical hydraulic jump process. The wall jet created after jet impingement along the solid wall is not responsible for triangular splashing. The process investigated depends on the degree of the Diesel jet development and is characterized by impingement of the jet core on the wall only. A hypothesis of a non-homogenous jet core has been formulated and verified to explain triangular splashing regions. For very small distances between nozzle and wall, the resulting splashing may be observed as a star-like three-jet structure. These jets, rebounding in three pre-dominating directions, will spread the preliminary circular splashing (just after wall contact of the primary jet) rendering the splashing geometry more and more triangular in shape until the transition time occurs.

1. INTRODUCTION

Under certain conditions of Diesel jet wall impingement the splashing region may be polygonal in shape (in the present report triangular shapes have been observed) contrary to expected circular splashing geometries.

Very intense and detailed experimental investigations have been performed to explain the phenomenon of polygonal (e.g. triangular) splashing geometries observed in a high velocity (Diesel) jet impingement on a solid wall, and main results are summarized in this paper. The present work explains the physical reasons of the observed phenomenon and outlines a possible background for understanding the process. In the first attempt it could be expected that the polygonal structures may be explained by hydraulic jump theory. In such a process polygonal structures have also been observed, as described in the literature [1-3]. There are different types of hydraulic jump resulting in different splashing geometries (circular or polygonal). The type I jump is the standard circular hydraulic jump in which the surface flow will go radially outwards everywhere (Fig.1a).

The interior flow, too, is radially outwards everywhere except within a recirculating region just downstream of the jump [4] (Tani (1949)). Furthermore, the type IIa jump is similarly marked by a subsurface ‘separation bubble’, but also by a region of reversed surface flow adjoining the jump (Fig.1b). As the outer depth increases further, the jump transforms into a Type IIb jump marked by a tiered or ‘double-jump’ structure (Fig.1c) [1] (Bohr et al (1996)). A key observation is that the axial symmetry-breaking instabilities occur exclusively for Type II jumps [1],[3],[5].

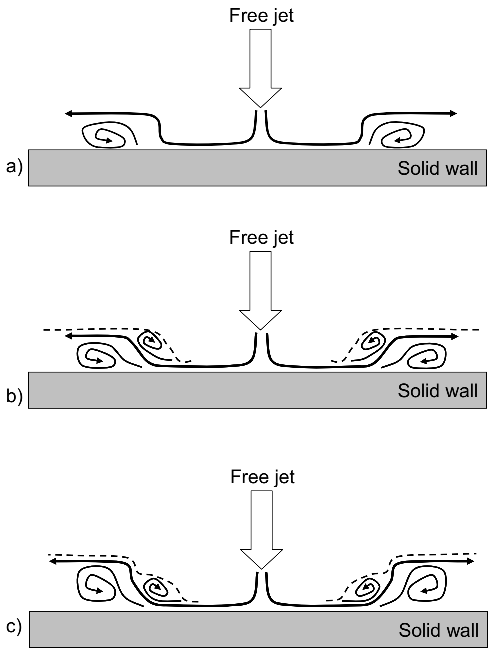


Figure 1. Model of hydraulic jump (based on the model taken from [5]): a- hydraulic jump of the type I; b- hydraulic jump of the type IIa; c- type IIb.

Experiments performed by the authors and test conditions used in the present investigation (injection in oil bath and air under atmospheric conditions) have indicated that the obtained results cannot be described or explained by the

hydraulic jump theory. As shown in this paper, there is no influence of the wall jet or of the vortex on the polygonal splashing structures, as would be indicated by the hydraulic jump theory.
The present investigation, however, concentrates exclusively on the impingement region and on the geometry of the splashing process.

2. JET WALL IMPINGEMENT

For analysis of the impingement of a Diesel jet on a wall a model is considered in this report, as presented in Fig.2. The following characteristic regions of the jet-wall impingement process have been selected:

Region 1: free jet region characterized by jet geometry, propagation velocity and atomization.
Region 2: impingement region characterized by impingement velocity, impingement shape and area, impingement angle (relative angle between free jet and the wall).
Region 3: main wall-jet region characterized by radial velocity, jet length and thickness.
Region 4: wall-jet vortex region characterized by vortex position with respect to impingement region, vortex size and angular velocity.
Region 5: leading edge defining the edges of the impingement process.

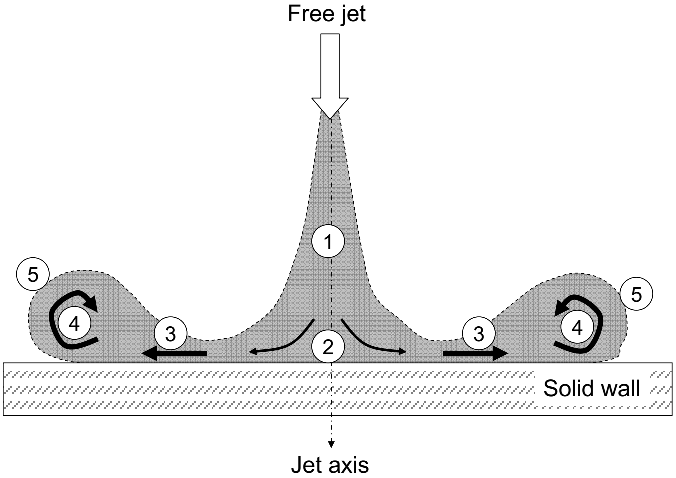


Figure 2. Model of jet impingement on a solid wall: 1-free jet region; 2-impingement region; 3-main wall-jet region; 4-wall-jet vortex region; 5-leading edge.

It is expected that for an axially symmetric Diesel jet the wall impingement results in a circular splashing region-see Fig.3.

3. MEASUREMENT TECHNIQUE

In order to investigate Diesel jet interaction with a solid wall, a special low-pressure test chamber has been used with two different surrounding fluids (air or oil)- see Fig.4. Diesel injection in oil has some special features: no atomization may be observed during free jet formation and its propagation throughout the chamber volume (single-phase system in liquid); any fuel vaporization process is practically eliminated.

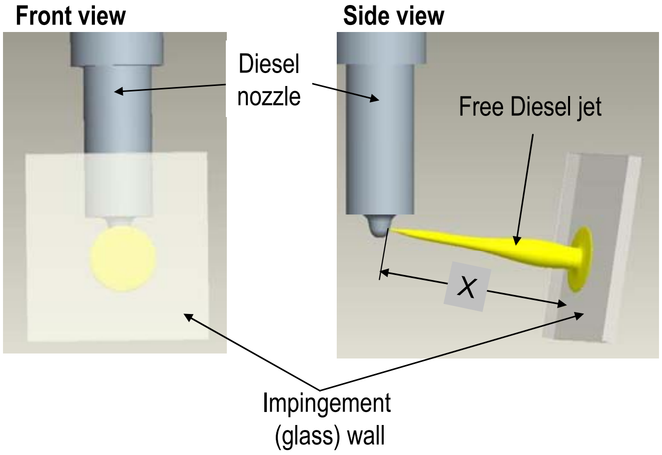


Figure 3. Circular splashing of the Diesel jet on a solid wall: top-overall view; bottom-at different time periods after jet wall contact.

For taking measurements at high resolutions with respect to time, a black-and-white CDD camera with an external trigger (synchronized with injection timing) and with shutter speeds from 1 to 1000µs has been used. In the investigations reported here, an exposure time of 100µs has been applied. Additionally, the signal phase could be shifted with respect to the injector trigger signal. A detailed description of the system is given in [6,7].

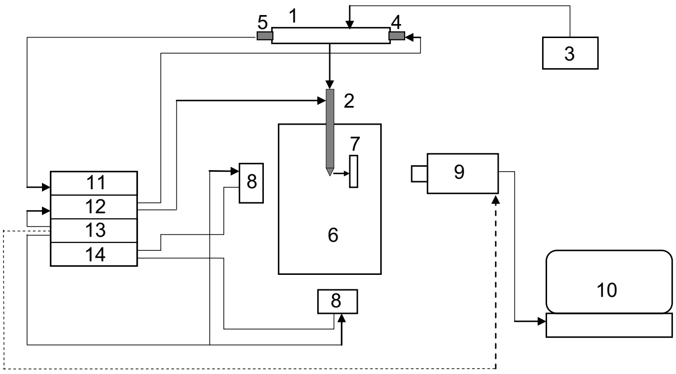


Fig.4. Test rig for investigating Diesel jet impingement on a wall: 1 - common rail; 2 - Diesel injector; 3 - high pressure CR pump; 4 - pressure valve; 5 - pressure control valve; 6 - test chamber; 7- solid wall; 8 - stroboscopes; 9 - CCD camera; 10 - software and image analysis; 11 - pressure monitoring; 12 - injector control unit; 13 - trigger signal; 14 - phase control (timing).

The quantities calculated from the recorded pictures are obtained digitally, based on the intensity distribution of the recording pictures. The pictures with injection are then compared with a reference picture (“background” without jet) having the resolution of a single pixel (pixel size was below 100µm). There are different nozzles used in the present investigations. Most of the performed experimental investigations have been performed using a special two-hole nozzle (180deg).

4. INDICATION OF POLYGONAL (TRIANGULAR) SPLASHING IN DIESEL-JET WALL IMPINGEMENT

It is expected that in the front view of the wall impingement, the resulting impingement region of a circular jet will be circular in shape. The resulting circular impingement region grows with time after impingement and practically does not change its shape with time but remains more or less circular in shape (fig.5).

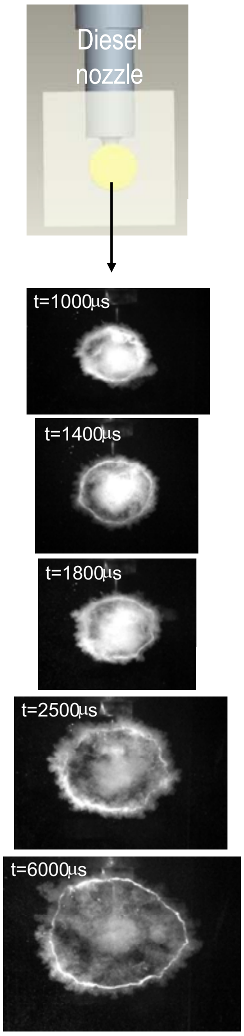


Figure 5. Circular splashing of the Diesel jet on a solid wall at different time periods after jet wall contact (measured in oil)

At a reduced distance between nozzle and the solid wall the observed splashing region (for a two-hole nozzle) is still circular at the time just after the impingement moment. However, at time intervals longer than the transition time, the impingement region changes its geometry and clearly shows triangular regular shapes (a polygonal structure with corners), as shown in Figure 6 for X=7mm. At the beginning of the impingement process the splashing region is clearly circular in shape. This shape may be observed until approximately 1000µs after wall contact (for X=7mm). At longer time intervals (t>1000µs), the splashing region becomes triangular in shape and does not change this geometry even at much later time positions.
The time after jet wall contact at which the splashing shape changes from circular to the triangular one is defined as a transition time. This transition time depends on the injection pressure (jet velocity) and the distance from the wall, as plotted in Figure 7.

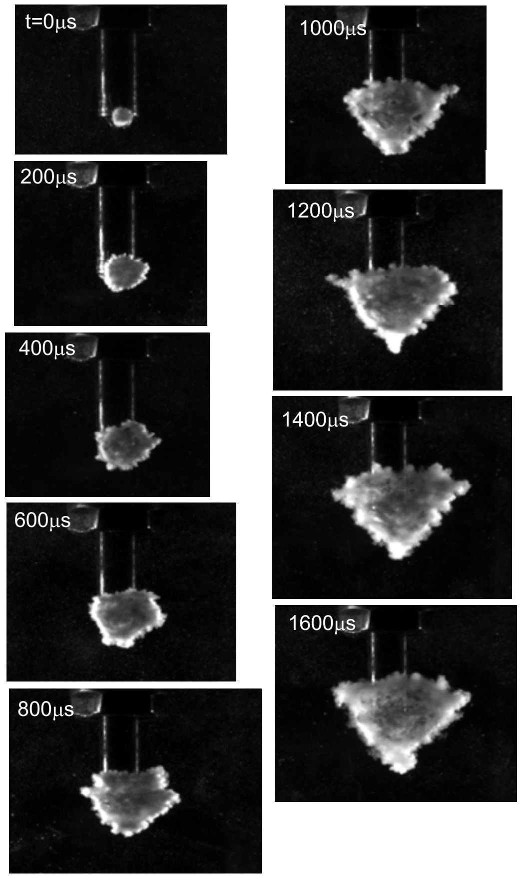


Figure 6. View of splashing shapes in Diesel-jet impingement on a solid wall at X=7mm (in oil) and p_{inj}=800bar at different intervals after wall contact (t), τ_{inj}=1500µs.

The transition time changes linearly with the distance from the wall and reduces with increasing injection pressure (jet velocity). After creating the first polygonal structures the splashing geometry remains triangular in shape and is independent of the time after transition time.

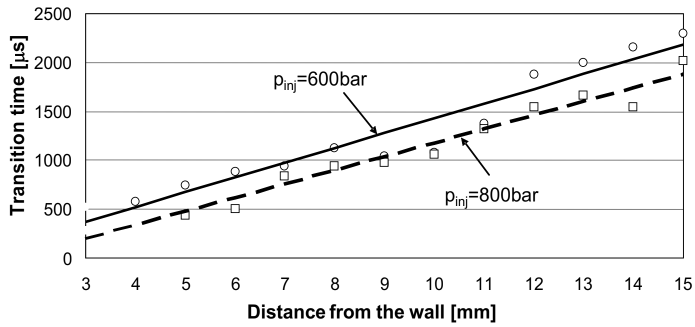


Figure 7. Relationship of transition time versus distance from the wall X at two injection pressures (data for injection in oil).

Triangular splashing (for two-hole nozzle) has been observed over a very wide range of injection pressures from approximately 300bar up to 1400bar. The mean diameter of the splashing region at a distance of X=7mm for two-hole nozzle is shown in Figure 8 as time-dependent after trigger signal (injection). For lower distances from the nozzle the mean diameter of the splashing region is only very weakly dependent on injection pressure. Similar observations have been made by investigation of the contour line length of the impingement region. No indication of any discontinuity or irregularity in the contour line length, related to the shape transition, could be observed.

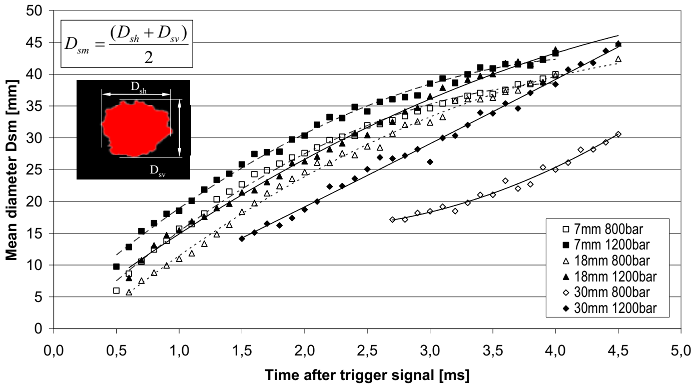


Figure 8. Mean diameter of the splashing region in Diesel-jet impingement on a solid wall in oil for two injection pressures (800bar and 1200bar) and three distances between nozzle and wall.

The sensitivity of triangular splashing shapes with respect to fluctuations in relative angular location between impinging jet and wall has also been investigated (this is very important for a hydraulic jump process). Experiments have been performed in such a way that the wall was inclined to the left and to the right with respect to the impinging jet axis, and the jet splashing process was then recorded. The test condition has been chosen in such a way as to obtain triangular splashing shapes with the wall being perpendicular to the impinging jet axis. The splashing regions (triangular shapes) were practically not changed in shape but the relative location between nozzle and triangle observed through the transparent wall from the front was moved, according to the relative incline of the wall.

5. EFFECT OF THE JET CORE

It has been assumed that a stationary free axisymmetric jet is divided into three regions [8]: initial region, transition and fully developed region. On this basis two characteristic parts of the jet are selected in this paper: jet core and the jet itself (see Fig.9). Typical localizations of impingement wall with respect to the jet core length are also indicated in this figure.
It will be important to recognize which of these two parts (especially the jet core) plays a critical role in the impingement process and in the formation of triangular splashing shapes. Close to the nozzle outlet the jet is not fully developed yet, and a jet core is selected as a main part of the free jet.

Typical localizations of impingement wall with respect to the jet core length are also indicated in this figure.
It will be important to recognize which of these two parts (especially the jet core) plays a critical role in the impingement process and in the formation of triangular splashing shapes.

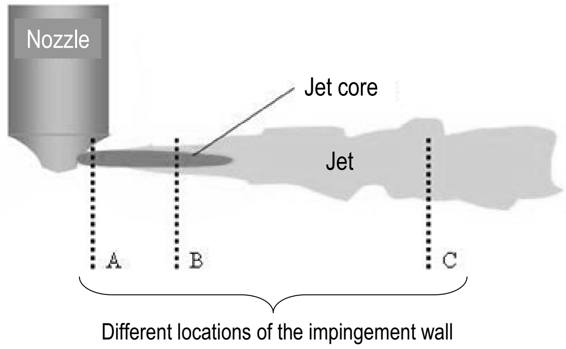


Figure 9. Structure of Diesel jet based on the model of axisymmetric, stationary jet formation.

5.1. Indication of the role of the jet core

As described in the literature, for a stationary jet this core may be observed at a distance on the order of 10 to 20 nozzle diameters. Observations made by the present authors suggest much wider penetration of the core. With increasing distance from the nozzle outlet and with increasing time after injection start the free jet reaches fully developed conditions (velocity profile). In order to verify this hypothesis (jet core effect) special experiments have been performed with a cube - see Fig. 10.

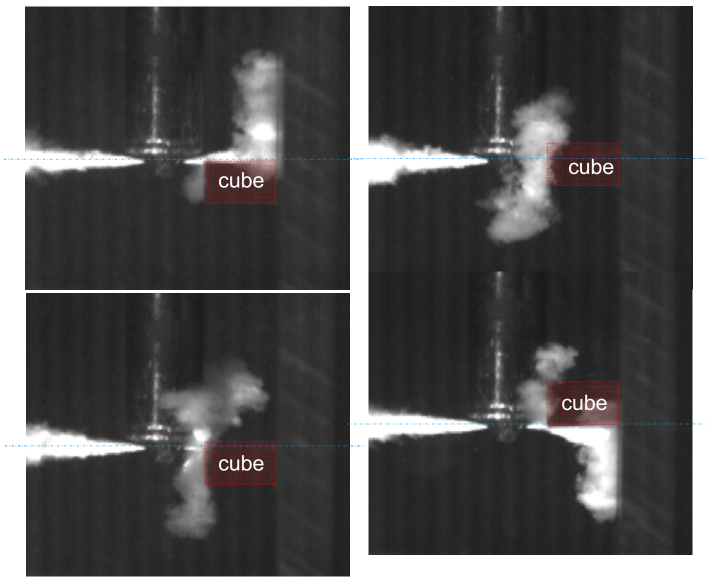


Figure 10. Characteristic jet impingements on the cube (side view).

This experiment concerns jet impingement on a small cube. This cube, with dimensions of 5mm x 5mm x 7mm, is mounted on the solid wall and the Diesel-jet impingement process is investigated for different locations of the cube with respect to the jet (core) axis.
The cube was positioned vertically in such a way that the disturbance (cube) could be located in the impingement region close to the jet axis as well as wide away from the splashing region. The injection pressure, injection duration and time after trigger signal were kept constant for all investigated cube locations.
Two characteristic situations may be selected in this experiment. The jet partly impinges on the cube (Fig.11a),

and the jet completely impinges on the cube surface (Fig.11b). In the latter case the impingement process is not supported by the wall for development of wall jet, as is the rule with hydraulic jump. The triangular splashing occurs in a “free space” without support of the wall. This indication of the role of jet core in creating triangular splashing will further be supported by Diesel-jet impingement on a solid wall observed in air under atmospheric pressure conditions.

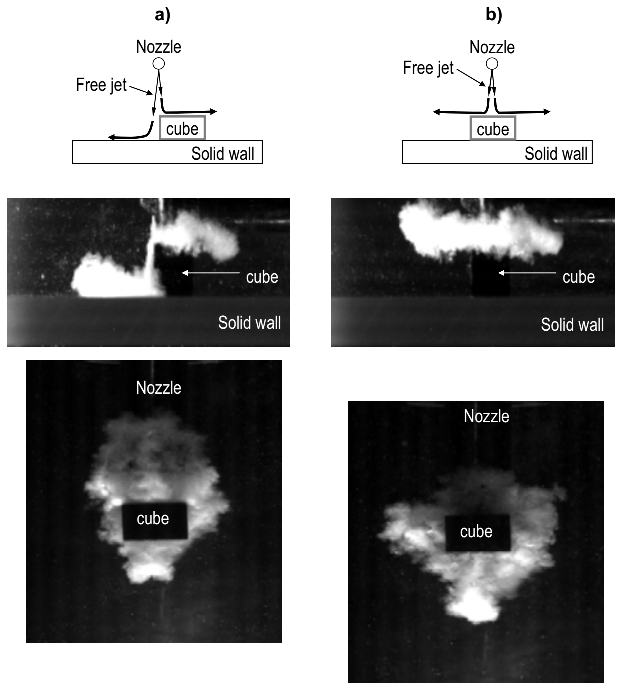


Figure 11. Two characteristic jet impingements on the wall with a cube: a- jet partly impinges on the cube; b-jet fully impinges on the cube.

5.2. Special experiments with pin: verification of jet core hypothesis

Experiments with a cube indicate that the jet core is a key parameter in generating the triangular (polygonal) splashing structures. In order to support this hypothesis another experiment has been designed in which a jet core impinges on the sectional area of a very small pin in proximity of the nozzle outlet (d=1mm and 2mm) – see Fig.12.

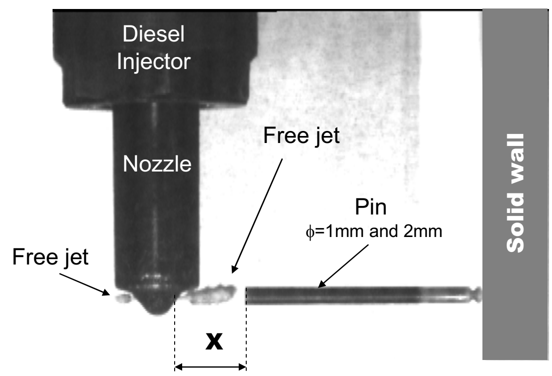


Figure 12. View of experimental configuration for investigation of Diesel jet impingement on a pin.

For relatively small distances of the pin with respect to the nozzle outlet (up to X=6mm) the jet core completely impinges on the pin surface resulting in triangular shapes, as indicated in Figure 13.

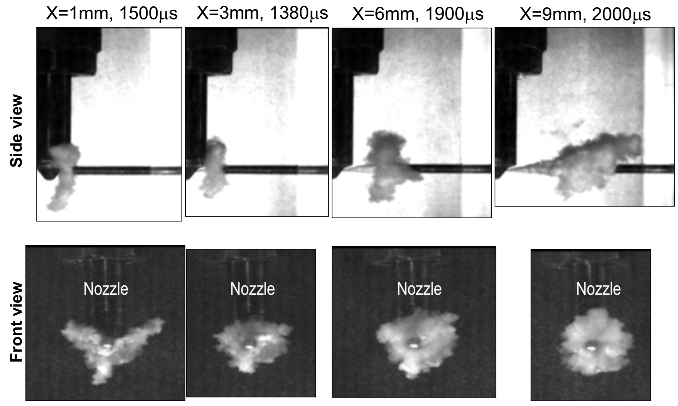


Figure 13. View of Diesel-jet impingement on the pin for different distances from the nozzle (X) at selected times after wall contact at p_{inj}=600bar (two-hole nozzle, injection in oil).

The upper pictures represent a side view, and the bottom pictures show a front view of the process. The pictures are plotted at different time intervals after pin contact. The larger distance from the nozzle the smaller is impingement area of the pin comparing to the jet cross-sectional area. At very large distances the pin can be overflowed by the Diesel jet, however still splashing of the Diesel jet may be observed. For the next experiment the pin diameter was reduced to d=1mm and the distance between nozzle outlet and the pin impingement surface was fixed at X=1mm (Fig.14).

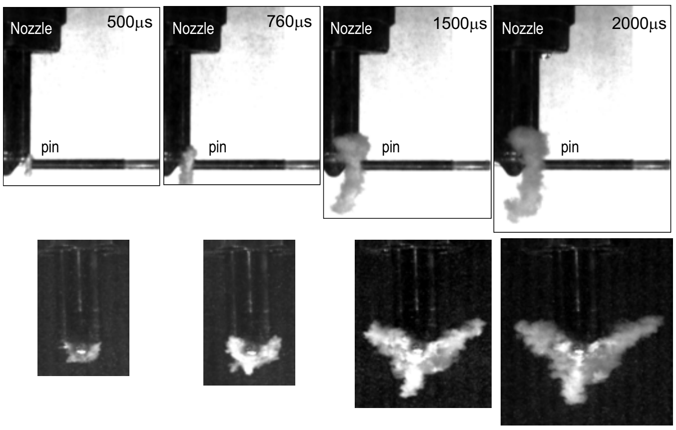


Figure 14. View of Diesel-jet impingement on the pin for different times after wall contact at p_{inj}=600bar and X=1mm (two-hole nozzle).

Such close to nozzle pin location suggests that the jet core only will impinge on the pin surface, whereas the jet itself is not developed yet. Again the upper pictures are observed from the side, and the bottom pictures represent a front view of the impingement process. The pin is positioned so closely to the nozzle outlet that the jet radially spreading after impingement is in its upper part blocked by the nozzle. As indicated in this figure the splashing process results in a star-like structure characterized by three pre-dominating jets (this effect has also been observed by impingement in air). These jets are very stable in time after pin contact.

The results presented support the hypothesis of a non-homogeneous core (inhomogeneity probably due to cavitation inside the nozzle) which is schematically formulated in Figure 15.

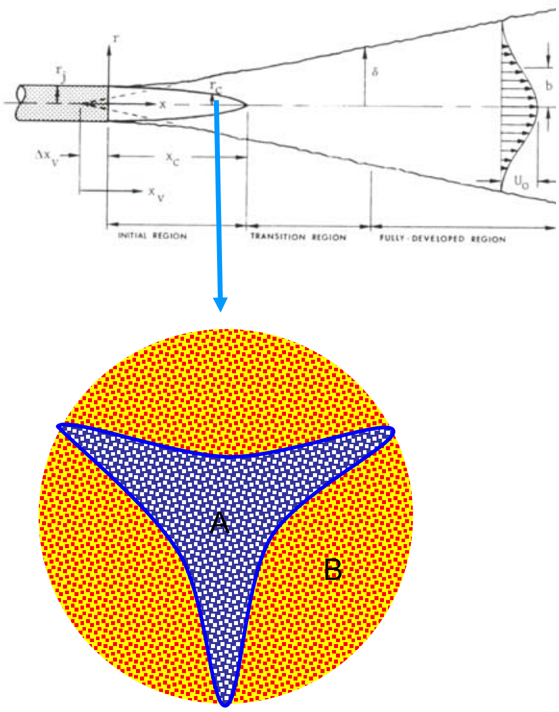


Figure 15. Hypothetical model of homogeneous and non-homogeneous jet core: A-non-homogeneous core in the form of "star" geometry; B-homogeneous jet core (circular)

This hypothesis suggests that if the jet cannot develop after leaving the nozzle and impinges on the wall (e.g. impingement on the pin) the resulting splashing could be star-like in geometry having three pre-dominating directions (jets). This can also be supported by observations made in air where the core length is much higher than in oil (owing to the oil's high density) - see Fig.16.
First insight in the splashing process of the Diesel jet on a solid wall in air at atmospheric conditions indicates three pre-dominating jets which are observed after a given time after jet-wall contact. At time intervals below approximately 600µs after jet-wall contact the splashing region is circular and shows homogeneously distributed radial jets propagate outwards from the splashing centre.
During this time the core of the jet has not yet reached the wall and there is no jet-core contact with the wall. To support this observation the jet in air has been visualized from the side view angle with the negative pictures giving better contrast for analysing the jet structure (see Fig.17).

At 800µs after wall contact the jet core has already impinged on the wall and three pre-dominating jets may clearly be observed. Similar pictures are obtained as the injection process continues, indicating that these three jets are generated in an area close to the jet axis and radially spread from the impingement centre.

At the time interval of approximately 2200µs the nozzle closes and the three jets start to separate from the impingement centre and a jet core is no more visible in the jet. For longer time intervals the three jets detach themselves completely from the jet axis area and propagate radially outwards from the impingement centre.

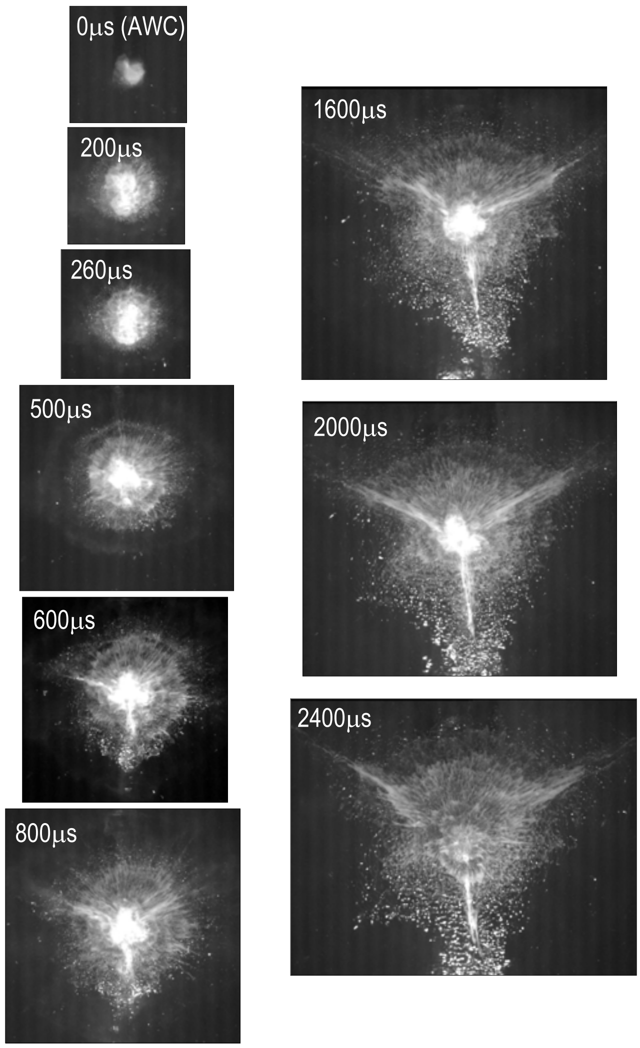


Figure 16. Front view of the Diesel-jet impingement on a solid wall in air at p_{inj}=600bat, τ_{inj}=1500µs, X=26mm as a function of time after wall contact (two-hole nozzle).

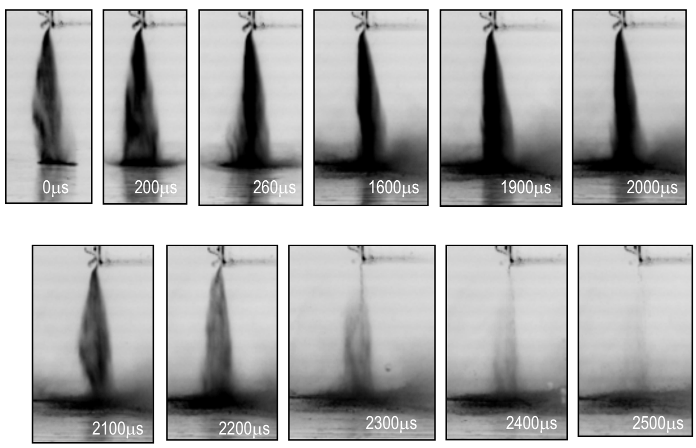
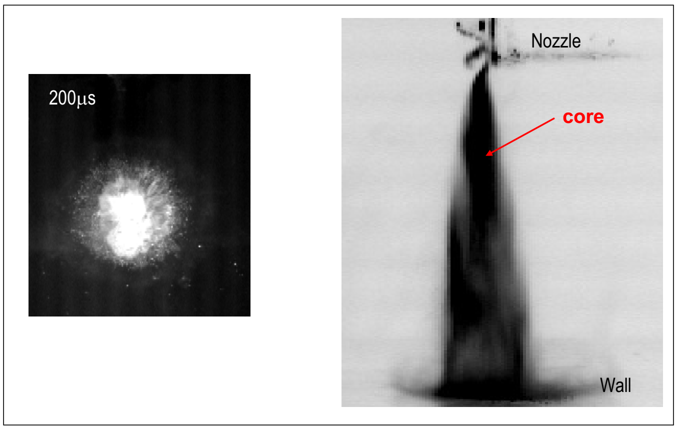


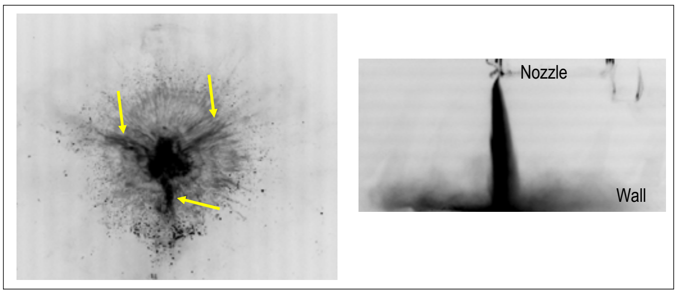
Figure 17. Side view of the Diesel-jet impingement on a solid wall in air at p_{inj}=600bat, τ_{inj}=1500µs, X=26mm as a function of time after wall contact (two-hole nozzle) - back-light illumination.

Five characteristic phases of the Diesel-jet impingement process based on jet-core impingement, are distinguished as described below.

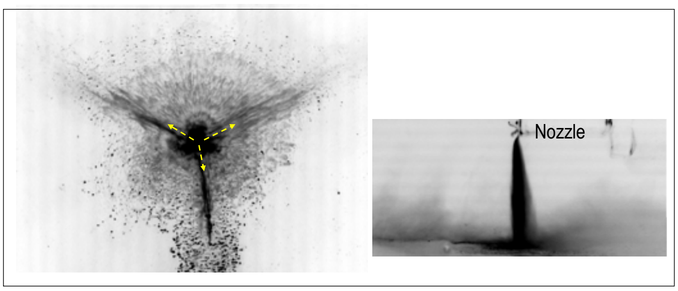
Phase 1: Formation of the jet core in space between nozzle and the wall (homogeneous circular splashing);



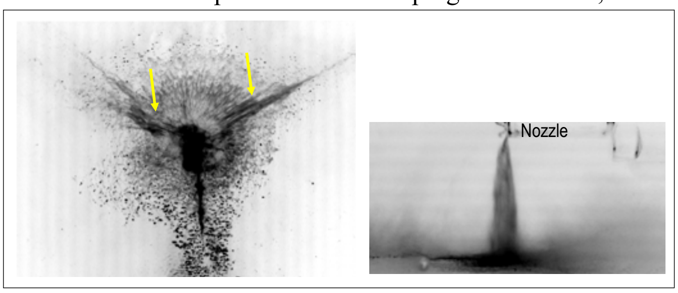
Phase 2: Jet core impinges on the wall: creation of three pre-dominating jets;



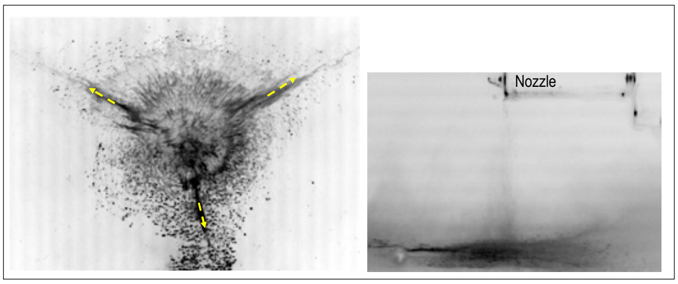
Phase 3: Continuing injection process (nozzle still open): three jets remain attached to the impingement centre;



Phase 4: Nozzle starts closing: three jets start to separate from the impingement centre;

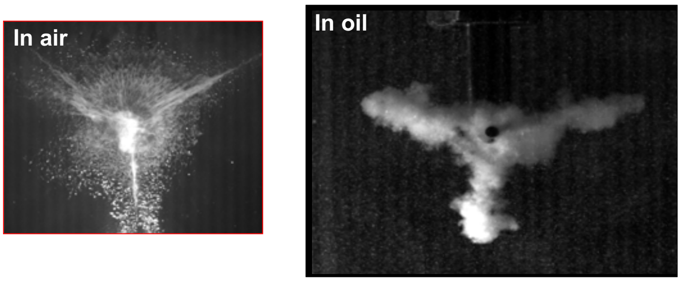


Phase 5: Nozzle is closed: three jets completely detach themselves from the impingement centre.



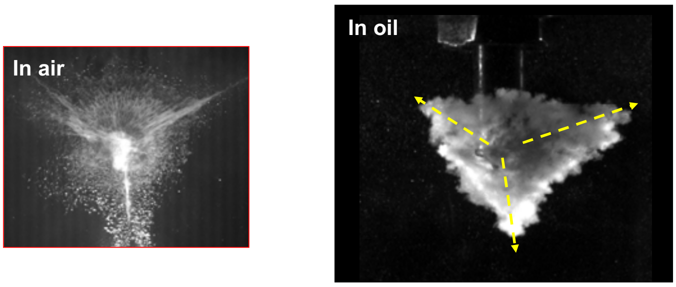
Careful analysis of the pictures obtained by injection in air indicates that the three-jet configuration corresponds to the triangular splashing observed in oil. The highlighted five phases of the process point to the existence of transition time and may explain the time-dependence of the triangular splashing shapes observed in oil. On the basis of intensive experimental investigations the following points have been selected to support the correlation of investigated process in air and oil under atmospheric conditions.

Correlation 1 Three pre-dominating jets have been also observed in oil for jet impingement onto a small pin:



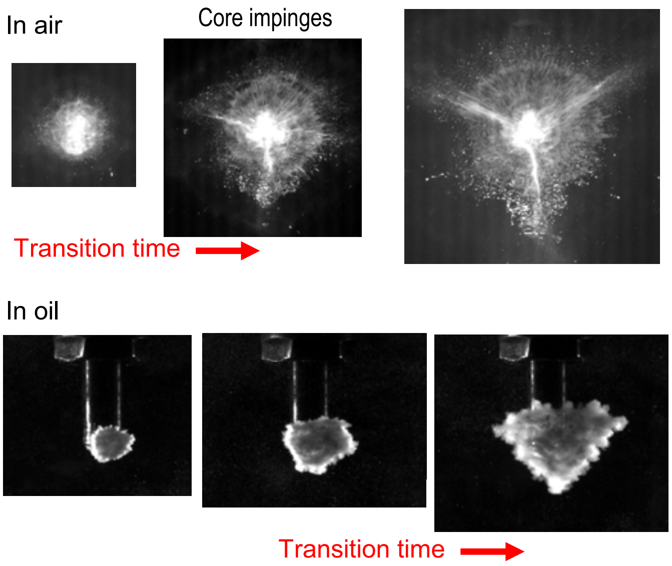
The fact that three jets have been observed in both air and oil renders the results independent of the surrounding fluid conditions.

Correlation 2 Spatial orientation of these three jets corresponds to triangular splashing observed in oil:



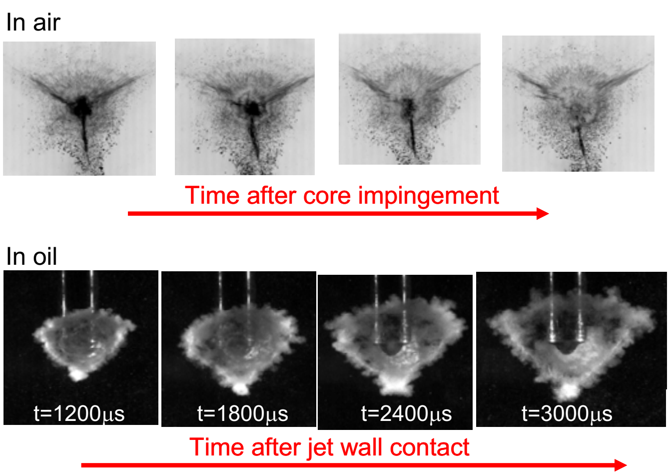
It has been found that in spite of significantly different test conditions and different jet velocities in oil and air, the three jets are similar in both investigated fluids. Moreover spatial orientation of these three jets corresponds to triangular splashing observed in oil.

<u>*Correlation 3*</u> *Jet-core impingement and explanation of transition time:*



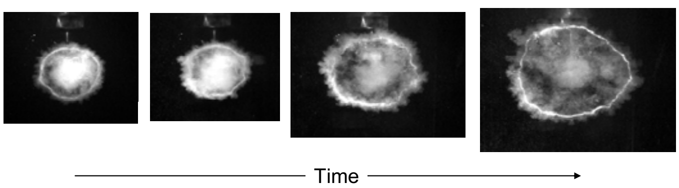
It has been found that the three jets are a result of jet-core impingement on a solid wall. It is necessary to stipulate the existence of some transition time required for creating the triangular splashing observed in oil. The transition time observed in oil correlates well with the timing of the jet-core initial contact with the wall.

<u>*Correlation 4*</u> *Jet-core impingement and independence of triangular shapes of durations beyond transition time:*



Temporal behaviour of three jets observed in air explains why the triangular splashing observed in oil is independent of the duration exceeding transition time. After jet core impingement on the wall, three observed jets do not change their geometrical configuration and form triangular splashing shapes observed in oil independent of time.

<u>*Correlation 5*</u> *Jet-core penetration length and circular splashing (long distance from wall):*



For wall distances larger than jet core penetration length the jet splashing on the wall is circular in shape, according to the jet's axisymmetric geometry).

6. CONCLUDING REMARKS

As described in the paper the Diesel-jet wall impingement on a solid wall may result in circular or triangular (polygonal) splashing shapes. This effect depends on the geometrical configuration, time and nozzle geometry. For the nozzle under investigation three pre-dominating jets have been observed in air corresponding to the triangular splashing geometries recorded in oil.
This process is almost independent of the injection pressure, injection frequency or of the injection duration. Additionally, the triangular splashing shapes are observed at a given transition time after Diesel-jet wall contact. This time is dependent on the distance from the wall and the injection pressure. The process is dependent on the distance from the wall. The observed process is not a typical hydraulic jump process and cannot be explained by the hydraulic jump theory. The impingement angle has practically no influence on the triangular splashing shapes. The wall jet formed after jet impingement along the solid wall (hydraulic jump) does not play any part in the formation of a triangular splashing geometry. The process of triangular splashing geometry has been observed in Diesel injection in air at p=1bar as well as in an oil bath.
The described process depends on the degree of Diesel-jet development and is practically defined by the jet-core impingement on a wall only. This jet core is not necessarily homogenous and its impingement on the solid wall results in three pre-dominating directions giving rise to triangular splashing regions.

References

[1] Bohr T, Ellegaard C, Hansen A.E., Haaning, A. 1996 Hydraulic jumps, flow separation and wave breaking: an experimental study *Physica* B 228, 1.
[2] Bush, J.W.M., Aristoff, J.M. 2003, The influence of surface tension on thecircular hydraulic jump, J. Fluid Mech., 489, pp.229-238.
[3] Bush, J.W.M., Aristoff, J.M., Hosoi, A.E. 2006, An experimental investigation of the stability of the circular hydraulic jump, J. Fluid Mech., 588,pp.33-52.
[4] Tani, I. 1949 Water jump in the boundary layer. J. Phys. Soc. Japan 4, 212–215.
[5] Ellegaard, C., Espe, A., Haaning, H.A., Hansen, K., Marcussen, A., Bohr, T., Hansen, J.L., Watanabe, S. 1999, Cover illustration: Polygonal hydraulic jumps, Nonlinearity 12 , pp. 1–7.
[6] Weclas, M., Faltermeier, R. Diesel jet impingement on small cylindrical obstacles formixture homogenization by late injection strategy, Int. Journal of Engine Research, vol.8, Nr.5 2007, pp..399-413.
[7] Weclas, M. 2008, Some fundamental observations on the Diesel jet "destruction" and spatial distribution in highly porous structures, Journal of Porous Media, vol. 11, iss.2, 2008, pp.125-145.
[8] Witze, P.O. 1974, A study of impinging axisymmetric turbulent flows: the wall jet, the radial jet, and opposing jets, PhD Thesis, University of California, Davis, December 1974.

.