# Wall impact of single droplets under conditions of DISI-Engines

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The processes during Droplet-Wall interaction are very important regarding the computational simulation of mixture formation in IC-engines. But especially for the conditions in DISI engines no reliable models are currently available. The main aim of the presented paper was to perform experiments under conditions as close as possible to real DISI conditions. A special test rig was designed to produce single droplets in the necessary velocity and diameter range and the impingement process was analyzed using a highspeed imaging system. The experiments were performed with varying primary droplet size, primary droplet velocity and surface temperature. Additionally two different liquids with properties close to real fuel were used. The impingement process was studied by means of a highspeed CCD-camera whereas the secondary droplet sizes and velocities were determined by image analysis technique.

## 1. Introduction

The modern engine concept of direct injection spark ignition (DISI) engines provides a significant potential for improvements regarding fuel consumption and consequently $CO_2$ emissions. On the other hand, clearly visible difficulties exist to reach recent standards with respect to the emission of unburned hydrocarbons. This is mainly due to the inhomogeneity of the mixture with local very rich areas in the mixture and pools of liquid fuel on the walls of the combustion chamber. They can be attributed to the interaction phenomena between the droplets of the spray and the walls of the combustion chamber. To improve the emission characteristics of DISI engines exact knowledge of these phenomena and reliable numerical design tools are necessary.

The goal of the whole DWDIE project (EU, 5$^{th}$ framework program) is the development of correlations, which allow reliable prediction of the mixture formation process, especially taking into account the effect of the interaction of fuel droplets with walls under the specific conditions inside a DISI engine. The presented study concentrates on single droplet impact on the hot piston surface of a DISI engine.

Investigations of the impact of single drops on solid surfaces have been presented in the open literature by various authors. Rioboo et al. [1] investigated the influence of surface roughness and wettability of the liquid/solid/gas system. Six possible impact regimes were identified and separated in Deposition, Rebound and Partial Rebound, as well as different forms of Splash. The influence of a change of various parameters regarding the primary droplets and the surrounding conditions was presented together with an overview of the sensitivity of the process to a change of these parameters.

For the investigation of the interaction between successive droplet impacts or the impact of a single droplet on a partially wetted wall, Kalb et. al. [2] used a droplet chain generator and a deflection unit, consisting of a charging ring, to remove unwanted droplets from the chain. Significant differences were found in comparison to the impact on dry surfaces or liquid layers. While in the latter case the splashing limit can be described by a critical Weber number, in case of a partially wetted wall, splashing is controlled by the spreading velocity at which the impacting droplet hits the sticking droplet on the wall. For completely wetted surfaces, Cossali et. al. [3] identified a Splash-Deposition limit. In this case the splashing is characterized by the formation of a crown with emerging jets that disintegrate into secondary droplets. Interdependencies between the number of these jets and the number of secondary droplets were identified and established. Samenfink et. al. [4] analyzed the interaction between droplets and a shear-driven liquid film on the surface, esp. with regard to the secondary droplet characteristics. From this investigation, a complete set of correlations to calculate the behavior of the secondary droplets was evaluated.

Regarding the impact of droplets on hot surfaces, the main emphasis found in the literature was put on the investigation of the "Leidenfrost point". Bernardin [5] e.g. performed detailed experiments to study the processes taking place at an impingement under Leidenfrost conditions. The Leidenfrost point is characterized by the immediate formation of a vapor layer that separates the droplet from the wall, if the wall is heated above the Leidenfrost temperature. This means, that the droplet doesn't get in direct contact with the wall during the impingement process. The characteristic outcome of a droplet impact above the Leidenfrost point, also referred to as the Film Boiling regime, was a Rebound. The Rebound in general is a dynamically driven phenomenon. The receding of the liquid disc, in which the primary droplet is deformed during impact, is driven by surface tension forces and damped by contact forces between liquid and wall. If the surface tension forces overweigh the contact forces, the liquid regroups to a distorted droplet and rebounds back from the wall. The size of the secondary droplet is equal to the primary one, only potential evaporation due to an elevated surface temperature can reduce the liquid mass of the droplet. The velocity is lower than the impacting velocity due to momentum loss during deformation of the droplet.

In general various authors published correlations to provide the capability to predict the results of an impingement of a droplet on a solid wall (see e.g. [6, 7, 8]). Almost any of these correlations were developed using large droplets of pure liquids or mixtures, in order to simulate fuel properties. Comparing the results of these correlations for the range of conditions and liquid properties relevant for DISI engines, significant deviations become obvious. Concerning the experimental conditions it seems that still not all influencing parameters were taken into account. Therefore, one main goal of the present study was to perform experiments under conditions as close as possible to realistic DISI engines.

## 2. Experimental Setup

The investigation of single droplet wall impingement under DISI conditions required the production of very small droplets (below 100 μm) with a high momentum (up to over 10 m/s) and the control of the impingement process on a wall element. In the presented study this wall element was cut from a real engine piston in order to stay close to reality. However, a further requirement was to allow different impact angles and surface structures, but these investigations are not presented here. To visualize the small droplets, an imaging system with a high magnification was necessary. Using a long distance microscope an image size of 0.6 x 0.5 mm could be realized, but at the same time a limitation of the depth of field to below 0.1 mm had to be accepted. This very small measurement volume caused extreme requirements to the spatial arrangement of the experiments. Additionally a very precise temporal control of the experiments was necessary, since the droplet impingement had to take place inside this volume at the time of exposure.

The generation of droplets with the above mentioned properties required a generator with features no commercially available device could offer. Due to this fact, a droplet generator which provided the necessary droplet size was combined with an aerodynamic acceleration device to match the required droplet velocity. This complete device is illustrated in the upper part of Fig. 1. The droplets were injected in a stratified air flow at comparable velocities and accelerated in a standardized nozzle. At the nozzle exit the droplets left the device in the center of a free jet. The design of the nozzle was optimized by means of numerous PIV measurements and CFD-calculations to assure that the droplets reach the required trajectories and velocities for the impingement.

Regardless the thorough construction of the accelerating device, minor deviation of the droplet trajectories could not be completely avoided. But as already mentioned, the measurement volume of the long distance optics was so small, that only very few droplets would have been detected inside the depth of focus without further optimization. Another important effect to avoid was the negative influence of the air motion in the vicinity of the impingement location at the wall due to the acceleration device. The trajectories of the secondary droplets would have directly been influenced by this stagnating flow yielding a strongly biased result. To solve these problems a droplet separator unit was designed, which is shown in the lower part of Fig. 1.

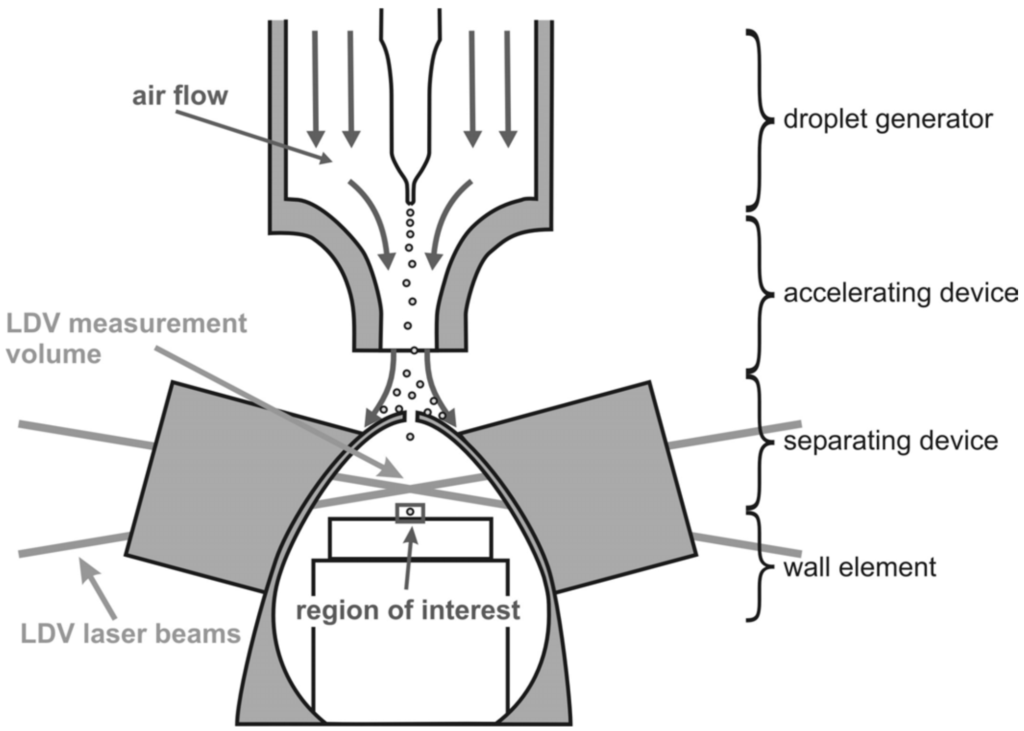


**Fig. 1:** Overview of the experimental test setup

A small orifice with a diameter of only 200 µm was placed inside the droplet/air flow before reaching the wall. By this unit, droplets aligned in the center of the flow were separated from the deviated ones and the main part of the air flow. The impingement location on the wall element was placed app. 10 mm underneath this orifice. Because of the stochastic nature of this separation the strict temporal relation between the droplet production and the impingement was lost, because of not knowning, which droplets passed the orifice and which didn't. To synchronize the impingement with the recording system and to assure the impingement in the correct location on the wall, the measurement volume of a 1D-LDV was positioned at a fixed distance between the wall and the orifice. As soon as a droplet passed the measurement volume the LDV processor produced a signal that could be used to trigger the imaging system. Additionally the LDV provided accurate information about the axial velocity of the primary droplets.

To investigate the complete impingement process both qualitatively and quantitatively, a highspeed CCD-camera system was used. As already mentioned, the high magnification was realized using a long distance microscope. The system was capable to record 16 images with interframing times down to one microsecond. This property in combination with a thorough calibration of the system to recover the real dimensions from the images, fulfilled the spatial requirements to resolve the small secondary droplets as well as the temporal requirements to resolve the complete impingement process.

The main feature of the experiments was to be conducted under conditions as close as possible to conditions inside DISI engines. However, the conflict between the using of real fuel and an optimal reproducibility of the results and the handling of the experiments led to the compromise of using Ethanol and Isooctane as test liquids. In terms of dimensionless numbers (Capillary and Laplace) a velocity of 4 m/s and a wall temperature of 18 % above the saturation temperature were set as basic parameters. The range in which the parameters were then varied is summarized in Tab. 1. The properties of the test liquids like saturation and critical temperature, density, surface tension and viscosity are given in Tab. 2.

**Tab. 1:** Boundary conditions of the experiments:

| Parameter | Boundary conditions |
|---|---|
| Droplet size | 50 µm / 80 µm |
| Wall temperature | 1.0 – 1.3 x $T_W/T_{sat.}$ |
| Liquid properties | Ethanol and Isooctane |

**Tab. 2:** Liquid properties of the used liquids:

| Liquid | $T_{sat.}$ [K] | $T_{crit.}$ [K] | Density [kg/m³] | Surface Tension [N/m] | Dyn. Viscosity [Pa s] |
|---|---|---|---|---|---|
| Ethanol | 351 | 516 | 773.2 | 0.022 | $1.05 \times 10^{-3}$ |
| Isooctane | 372.4 | 543.8 | 688.8 | 0.0182 | $0.466 \times 10^{-3}$ |

## 3. Results

A first series of exemplary visualizations of the impingement process is given in Fig. 2 showing the variation of the wall temperature as one of the fundamental influencing parameters in this study. At low temperatures, slightly above saturation temperature (upper row of Fig. 2), no secondary atomization occurs. The process is clearly situated in the regime of Deposition. Due to the temperature of the wall the liquid evaporates completely during app. 900 µs. If only the dynamic of the impingement is considered, all conditions investigated during the presented work and considered to be close to real DISI engine conditions led to complete

Deposition or in some cases to Rebound. No conditions leading to prompt Splash could be achieved. That leads to the consequence that all kinds of secondary atomization, which occurred during the presented investigation, can be attributed to the thermal influence of the hot wall. Rising the temperature to 18% above saturation temperature (2nd row in Fig. 2), the production and collapse of vapor bubbles inside the liquid pool on the wall can be observed in the images. Now, very small secondary droplets are produced during the collapse of the vapor bubbles. The time until the liquid is completely removed from the wall is app. 800 µs.

A further increase of the wall temperature to 25% above saturation temperature leads to a new phenomenon. At the beginning vapor bubbles are produced and collapsed, forming secondary droplets very similar as described before. But during this process the liquid levitates completely from the wall, finally merges again to one new droplet and leaves the wall. This comparably very large secondary droplet, with a size only a bit smaller than the primary one, leaves the wall very slowly (in the presented case 69 µm @ 0.1 m/s). This behavior shows some similarities to Rebound, but is not a dynamically driven effect, but a thermally driven one. Therefore this regime can be called *Thermal Rebound* regime. It shows some differences to similar investigations known from the literature but all performed using much larger droplets (see e.g. [9]). The conditions match the commonly used regime of Film Boiling, in which larger droplets than in the regime of Bubble Boiling are produced. But still all investigations performed with larger drops showed a high number of secondary droplets and thus naturally having a much smaller size than the primary ones. Consequently the limits between these regimes in the presented case were found between a wall temperature of 18 % and 25 % above saturation temperature.

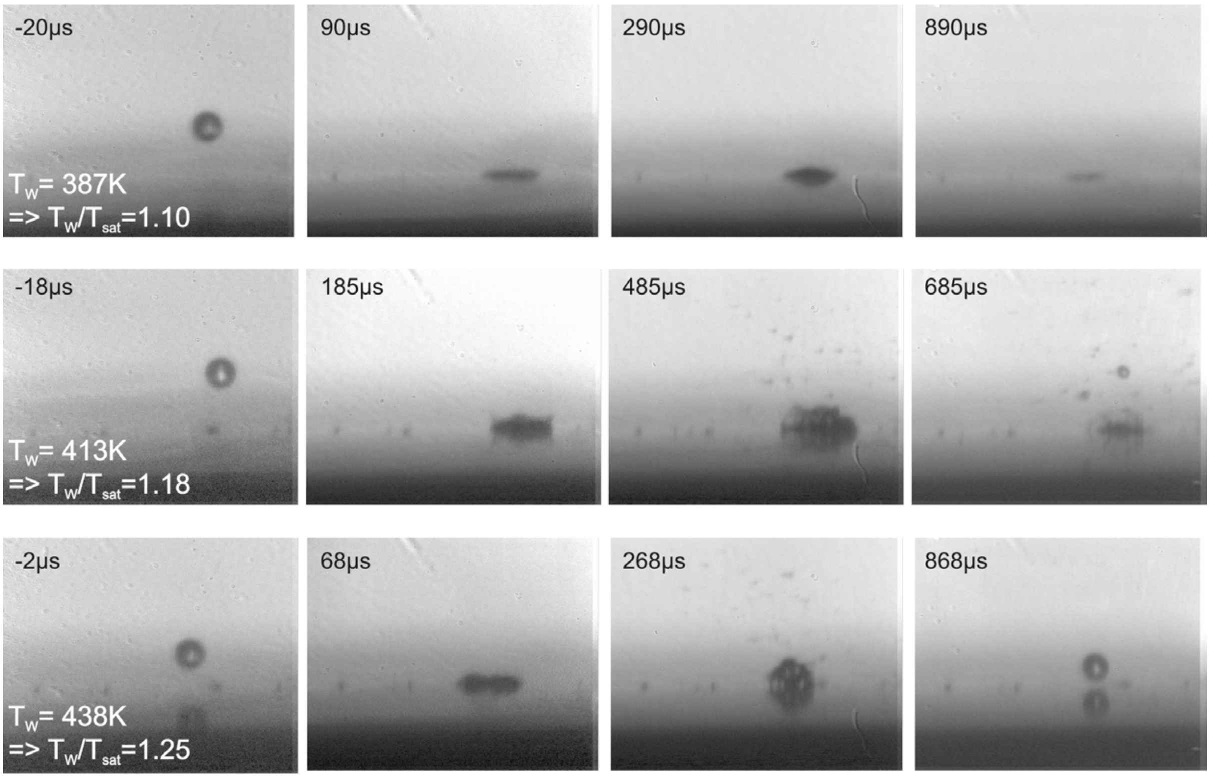


**Fig. 2:** Influence of the wall temperature (Ethanol, $d_{pd}$ = 80 µm, $v_{pd}$ = 4.2m/s)

Fig. 3 presents another very interesting feature of this phenomenon. It shows the impingement of an Isooctane droplet under conditions scaled to the ones in Fig. 2 regarding velocity and wall temperature. Only the Laplace number is about four times higher (4618 compared to 1234), which would be achieved in case of Ethanol, when increasing the droplet diameter to

300 µm. It is clearly visible in the figure, that the outcome of the impingement is quite different then. The Isooctane droplet disintegrates into several droplets and a few larger droplets leave the wall which is typical for the Film Boiling regime. From the facts already known it can be assumed that, depending on the liquid properties, this significant change in the phenomenon takes place when exceeding a certain droplet diameter. Starting with an impact of a larger droplet inside the Film Boiling regime and reducing the droplet diameter to change the impact conditions towards realistic DISI conditions, this regime change occurs before entering the range of DISI conditions. This underlines the significance of this phenomenon.

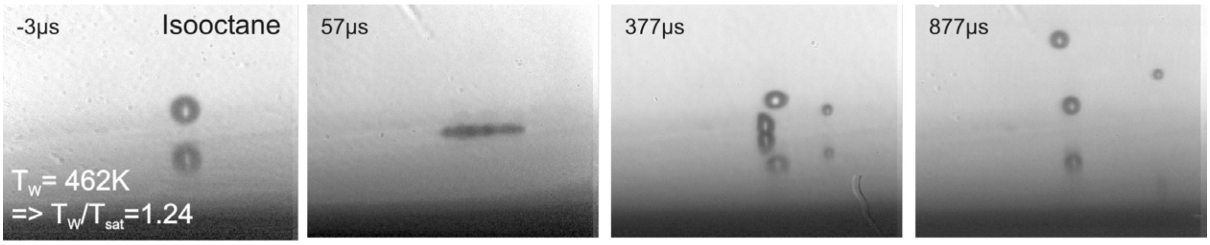


**Fig. 3:** Influence of liquid properties (Isooctane, $d_{pd}$ = 80 µm, $v_{pd}$ = 7.9 m/s, $T_W$ = 462 K)

For further investigation of the limits of the Thermal Rebound regime experiments were performed with Isooctane droplets of reduced diameter. Due to the design of the droplet generator, some deviations in the primary droplet velocity could not be avoided. Fig. 4 shows the impingement process for reduced droplet sizes for a wall temperature 30 % above saturation temperature of Isooctane. The first row shows a 44 µm droplet at 6.9 m/s. Similar to the behavior of the Ethanol droplet in Fig. 2 it spreads on the wall, reunites and levitates from the wall. The single secondary droplet has a diameter of 39 µm and leaves the wall at 0.3 m/s. This process can clearly be attributed to the Thermal Rebound regime.

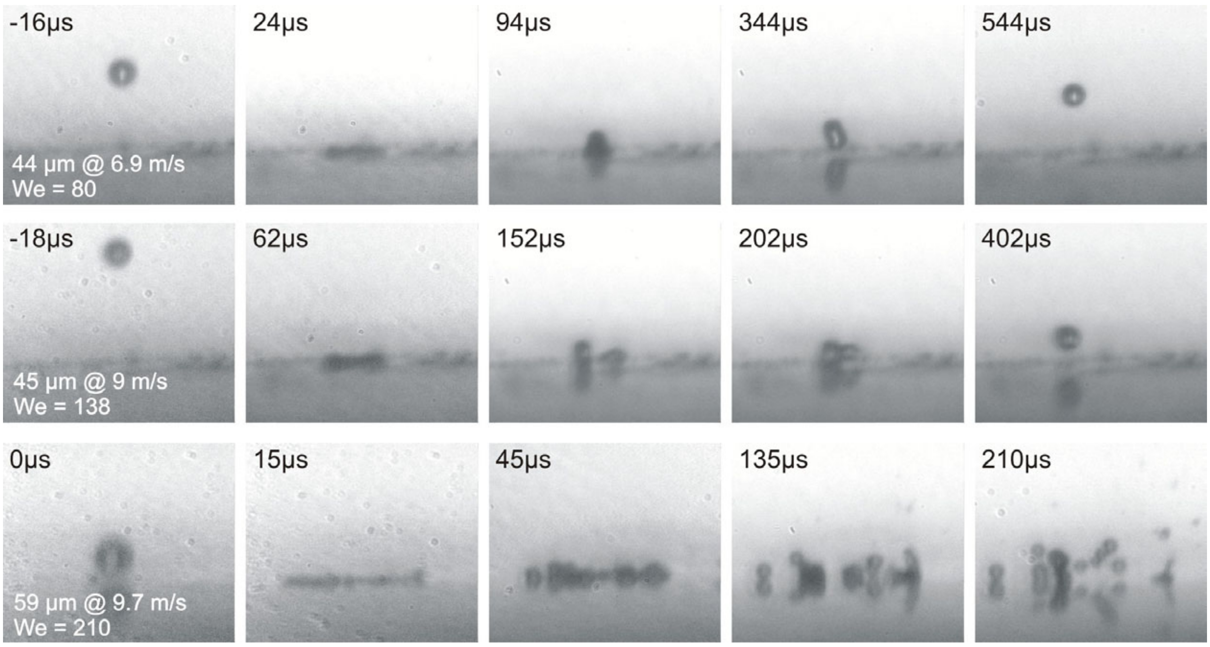


**Fig. 4:** Influence of primary droplet size (Isooctane, $T_W$ = 489 K)

Increasing the primary droplet velocity to 9 m/s, the middle row of Fig. 4 shows a similar behavior and the same regime. But the image in the center, 152 µs after impact, shows two droplets sitting on the wall, where in the upper row clearly only one compact liquid pool is visible. These two droplets levitate, as can be seen in the fourth image of the series, approach each other and merge. Only one secondary droplet, 37 µm in diameter, is formed and leaves the wall with a velocity of 0.2 m/s.

Increasing the primary droplet diameter to 59 µm with almost the same velocity leads to a significant change in the process, which is presented in the lower row of Fig. 4. The droplet spreads on the wall, disintegrates into several droplets and all these droplets leave the wall separately. This behavior can be attributed to the Film Boiling regime. This investigation showed that for Isooctane a limit between the Thermal Rebound and the Film Boiling regime exists between 45 µm and 59 µm in terms of primary droplet size (in terms of non dimensional numbers: La = 2598 / 3406, Ca = 0.23 / 0.248, and We = 138 / 210 resp.).

Further emphasis will be put on the determination of the boundaries of the Thermal Rebound regime, and the identification of the main influencing parameters. Regarding the primary droplet velocity two scenarios are possible. Some aspects could be identified, which lead to the assumption that the primary droplet velocity plays a minor role. The majority of impingement processes observed belong to the Deposition regime, if only the dynamic is considered. The spreading and the receding phase of the impact took each less than 40 µs. These phases are strongly affected by the impact velocity (for a detailed analysis of the spreading phases see e.g. [10]). But the processes of secondary atomization, which occur due to thermal conditions on the wall, need more time and start after the dynamically influenced processes already finished. But on the other hand, regarding the second scenario, it is possible, that especially the boundary between Thermal Rebound and Film Boiling is strongly affected by the size of the liquid disc on the wall formed by the impacting primary droplet. This disc is the outcome of the dynamic processes of advancing and receding phase during the spreading of the droplet. To get a more detailed insight to these phenomena, more experiments will be performed and analyzed in the near future.

Overall this regime seems to be very important especially for droplet wall impact under DISI conditions. A detailed knowledge might significantly improve the scaling of experiments with large droplets published in the literature to conditions of small fuel droplets and should help to find better correlations for the prediction of droplet wall interaction.

## 4. Summary

Due to the complexity of the process further investigation seems to be necessary for a complete understanding of droplet wall interaction. Especially for the conditions of DISI engines, where very small fuel droplets impinge on the hot piston surface, no reliable experimental data or correlations are available up to now. Therefore experiments under conditions as close to reality as possible had to be performed with special emphasis on the impingement of single droplets on dry heated surfaces. To meet the extreme requirements from the generation of small and fast droplets together with the necessity of acquiring highly magnified image series of the complete impingement process, a special test rig was designed and built.

The focus of the experimental results presented in this publication was on the identification of a new regime that could be referred to as typical for the DISI conditions. Under conditions where Film Boiling could be expected generating a number of large secondary droplets, only one secondary droplet of comparable size to the primary droplet could be observed. But no Dynamic Rebound could be identified, because the droplet spread on the wall and stayed there for quite a while. Then the liquid mass merged again and levitated from the wall forming a large single secondary droplet which left the wall slowly. This regime was referred to as Thermal Rebound.

By means of varying the primary droplet diameter one boundary of this regime could be identified for an Isooctane droplet. Further investigation will be necessary to identify the main influencing parameters and boundaries. Overall this process seems to be quite typical for single droplet wall impingement under DISI conditions, even the presented droplet sizes still represent the upper area of the ones occurring in DISI sprays. For a correct modelling approach of the mixture formation in DISI engines this phenomenon should be taken into account.

## 5. Acknowledgment

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## 6. References

[1] Rioboo, R., Tropea, C., and Marengo, M., *Outcomes from a Drop Impact on Solid Surfaces*, Atomization and Sprays, Vol. 11, pp. 155-165, 2001

[2] Kalb, T., Kaiser, H.-G., Kubitzek, A. M., Chaves, H., Obermeier, F., and Ebert, F., *Splashing-Phenomena due to Droplet Impact on Partially Wetted Surfaces*, ILASS-Europe, Toulouse, 1999

[3] Cossali, G. E., Coghe, A., and Marengo, M., *The Impact of a Single Drop on a Wetted Solid Surface*, Experiments in Fluids, Vol. 22, pp. 463-472, 1997

[4] Samenfink, W., Elsäßer, A., Dullenkopf, K., and Wittig, S., *Droplet Interaction with Shear-Driven Liquid Films: Analysis of the Secondary Droplet Characteristics*, ILASS-Europe, Manchester, 1998

[5] Bernardin, J.D., *Leidenfrost Point and Film Boiling Heat Transfer of Single Droplets and Sprays*, PhD-Thesis, Purdue University, 1996

[6] Mundo, C., *Zur Sekundärzerstäubung newtonscher Fluide an Oberflächen*, University of Erlangen-Nürnberg, PhD-Thesis, 1996

[7] Samenfink, W., *Grundlegende Untersuchungen zur Tropfeninteraktion mit schubspannungsgetriebenen Wandfilmen*, University of Karlsruhe, PhD-Thesis, 1997

[8] Weiss, D.D., *Periodischer Aufprall monodisperser Tropfen gleicher Geschwindigkeit auf feste Oberflächen*, University of Göttingen, PhD-Thesis, 1993

[9] Cossali, G.E., Marengo, M., Santini, M., and Watanabe, J., *Secondary Droplet Atomisation from Single Drop Impact on Heated Surfaces*, ILASS-Europe, Zaragoza, 2002

[10] Rioboo, R., Marengo, M., and Tropea, C., *Time evolution of liquid drop impact onto solid, dry surfaces*, Experiments in Fluids, Vol. 33, pp. 112–124, 2002