Droplet Wall-Film Interaction: Impact Morphology and Splashing/Deposition Boundary of Hyspin/n-Hexadecane Two-Component Systems

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Abstract
The present study investigates experimentally the impact morphology for permutations of the two-component system hyspin-hexadecane. The results of this study in terms of a model to predict the impact outcome, intends to improve the carbon footprint of Diesel engines. A comparative study is performed to highlight similarities (formation and ejection direction of secondary droplets) and differences (crown shape and evolution) between the splashing of the two permutations (hyspin droplet/hexadecane wall-film and hexadecane droplet/hyspin wall-film). An attempt is made to identify the most relevant parameters to explain these variances with particular regard to the wall-film properties. Related one-component experiments, employing hyspin and hexadecane, are performed to deepen the understanding of the impact morphology. Further, the experimental results are used to determine the onset of splashing. The experimental set-up, consisting of a two-perspective high-speed shadowgraphy imaging system, is briefly outlined. The impact morphology appears to be dominated by the properties of the wall-film. In particular its viscosity shows a major effect onto the crowns shape that shifts from conical to cylindrical with decreasing wall-film viscosity. An empirical correlation, based on the $K$-factor approach, for the splashing/deposition limit for the hyspin-hexadecane two-component systems is proposed, which covers the parameter range at hand. In accordance with present experimental evidence the original correlation is extended by applying an averaged viscosity of droplet and wall-film liquid, as well as the surface tension and density of the droplet, to define the Ohnesorge number.

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Introduction

The study of single droplet impact onto thin liquid films has a great number of industrial applications such as ink-jet printing, painting, pesticide spraying or combustion processes. For example, understanding of the underlying mechanisms and physical contexts of droplet wall-film interactions can be used to reduce diesel engine emissions, which is still a topic of high importance. An efficient strategy is to increase the exhaust gas temperature by post-injections. The major issue of this strategy is the oil dilution in the combustion chamber. During the post-injection the combustion chamber wall, covered with a lubricating oil film, is exposed to the injected diesel, since the piston has already moved down. The impacting diesel droplets dilute the oil film causing loss of lubrication performance. Furthermore, if the impact energy is sufficient splashing may occur, whereby droplets consisting of diesel and oil might be ejected into the combustion, increasing the engine emissions. Hence, the development of a model, capable of predicting the onset of splashing and the characteristics of the secondary droplets size distribution, is necessary for improving the carbon footprint of diesel engines. To date the understanding and modelling of one-component splashing is relatively well advanced. Cossali et al. [1], for example, described in detail the splash morphology and the splashing/deposition limit for water/glycerine solutions. For various alcohols and alkanes, Vander Wal et al. [2] compared the splashing morphology and proposed an alternative correlation for the splashing threshold [3]. A detailed review on the experimental, theoretical and computational aspects of droplet impacts onto thin liquid layers and dry surfaces can be found in Yarin [4]. Moreira et al. [5] give an overview on advances and challenges in explaining fuel spray impingement with special focus on the transferability and benefit of single droplet impact research on spray modelling. In contrast, the research on two-component droplet wall-film interactions is at the very beginning. Thoroddsen et al. [6] investigated the impact of water/glycerine droplets on thin ethanol films. They focused mainly on the mechanisms of crown and hole formation, which they attribute to Marangoni-driven flows. These flows are triggered by differences in surface tension according to them. Banks et al. [7] performed an experimental study to rule out the effect of droplet and wall-film viscosity for droplet impacts onto thin films. For a dimensionless film thickness of $\delta = 0.1$, they found that the crown formation appears to be related more strongly to the wall-film properties, whereas crown splashing had some dependence on the droplet properties.

A comparison of impact morphologies between the two-component system hyspin/hexadecane and the related one-component interactions, regarding the influence of wall-film thickness and viscosity, is presented in Geppert et al. [8]. The objective of this paper is twofold. First, to identify the influence of the wall-film liquid onto the two-component splash morphology and to establish a splashing/deposition limit valid for both two-component systems considered here. For these purposes, a precise strategy is followed. As a first step, we chose a miscible liquid combination with liquid properties at ambient conditions that are similar to the liquid properties of diesel and engine oil at combustion chamber conditions. The fluids of choice are: hyspin, hydraulic oil, as surrogate fluid for the diesel droplet and n-hexadecane ($C_{16}H_{34}$) as surrogate for the oil wall-film. In this way, we ensure that the resulting Weber and Ohnesorge numbers are representative of diesel engine operations. Second, the splash morphologies of the two-component systems hyspin/hexadecane and hexadecane/hyspin are compared. Third, the related one-component interactions of hyspin and hexadecane are consulted. In a final step, we describe the determination of the splashing/deposition limit out of an analysis of our experimental results.

The outcome of the droplet impact onto a wall-film is characterized by the dynamics of the impacting droplet (droplet diameter $D_0$ and impact velocity $v$), by the liquid properties of both, droplet and wall-film (viscosity $\mu$, density $\rho$ and surface tension $\sigma$), and by the wall-film thickness $h$. For the comparison of the experimental results five non-dimensional numbers were used: the dimensionless wall-film thickness

$$\delta = \frac{h}{D_0}$$  (1)

the Weber number of the droplet

$$We_d = \frac{\rho_d v^2 D_0}{\sigma_d}$$  (2)

the Ohnesorge number of the droplet

$$Oh_d = \frac{\mu_d}{\sqrt{\rho_d D_0 \sigma_d}}$$  (3)

the Ohnesorge number of the wall-film

$$Oh_f = \frac{\mu_f}{\sqrt{\rho_f h \sigma_f}}$$  (4)
and an alternative Ohnesorge number employing the average viscosity of droplet and wall-film liquid

$$\text{Oh} = \frac{1}{2} \left( \frac{\mu_f + \mu_d}{\mu_d D_0 \sigma_d} \right).$$

(5)

The non-dimensional time, relative to the moment of droplet impact onto the wall-film, is defined as

$$T = \frac{t v}{D_0}.$$  

(6)

Splashing takes place when the impact inertia exceeds viscous and surface tension forces. The formulation of the dependency for a one-component system can be obtained through dimensional analysis. In this regard the subscripts are dropped for the moment. The dimensional estimate is carried out by means of the wall-film height averaged Navier Stokes equations. The term corresponding to the impacting droplet inertia lies in the order of $\rho D_0 v^2$, while the viscous term can be estimated by $\mu D_0 v / l_{\mu}$ and the surface tension effect is of the order $\sigma h / D_0^2$. At this, the viscous length scale $l_{\mu}$ is chosen similar to the work by Pasandideh-Fard [9]. An analogy to a laminar axisymmetric stagnation flow is drawn for which the boundary layer is of the order $l_{\mu} \propto \sqrt{v D_0 / \nu}$.

The estimates reveal the condition for splashing to the inequality

$$1 \gg \sqrt{\frac{Oh}{We}} + \frac{\delta^2}{We}.$$  

(7)

For the present parameter range the inequality can be reduced to

$$K = W e^{5/8} Oh^{-1/4} > \delta,$$  

(8)

where the non-dimensional group $K$ is referred to as impact factor. In literature different choices exist for the $K$-factor, where the present is according to Mundo et al. [10]. The equivalent non-dimensional group $K^{8/5}$ is for instance applied by Cossali et al. [1] or Yarin et al. [11].

**Experimental Set-up and Method**

The experimental set-up is presented schematically in Figure 1. Its distinctive feature is that the droplet impact is observed from two perspectives. The set-up mainly consists of three parts: the droplet generation system, the impingement area and the imaging system. For the droplet generation, the so called dropper is employed. The resulting droplet diameter is about 2.5 mm. The maximum adjustable fall height in our experiments is 1.5 m. As a consequence the maximum droplet impact velocity is 4.5 m/s. The impact area consists of a thin metallic ring, that was stuck on a smooth glass plate. Its inner region is filled with a small amount of liquid, so that a wall-film of defined thickness is generated. A laser light barrier is used to trigger the imagine system. The droplet impact is observed and recorded from two different viewing angles and one high-speed camera (Photron Fastcam SA1.1 675K-M1). The frame rate of the camera was adjusted to 20,000 fps and the shutter speed to 1/16,100 s. The resulting sensor size was 896 x 320 pixels. The impact area was illuminated constantly with light emitting diodes. The shadow images of the front and lateral view of the impact area are redirected by several mirrors and focused by a prime lens ($f = 50 mm$), so that both images are projected next to each other on the camera sensor. An image scale of 1:4 is employed to enable the observation of the complete impact process. The optical paths of both views are depicted in Figure 1. The blue dotted line represents the optical path of the front view and the red dashed line represents the optical path of the lateral view. In the upper right corner of Figure 1 a two-perspective image of a Lego® manikin is shown. The lateral view and front view are surround red (dashed), respectively blue (dotted). For a detailed description of the set-up see Geppert et al. [8]. In contrast to the set-up in [8] the determination of the wall-film thickness is improved. A commercial device of the Micro-Epsilon company is used. The device is based on the confocal chromatic imaging (CCI) technique, which allows the non-intrusive distance measurement. The optical probe acts both as emitter and receiver. It emits white light, which is split by controlled chromatic aberration into an interval of focal points depending on the monochro-
matic wavelengths. The receiver detects the light that is reflected back from a surface positioned in this interval and analysis its spectral distribution. Thereof, the distance of the surface relative to a reference plan is obtained. For the determination of the wall-film thickness two distance measurements are performed simultaneously. The incident light is reflected at the interface between air and liquid as well as at the interface between liquid and solid. The resulting distances are subtracted from each other to determine the wall-film thickness. A detailed description of the CCI-technique can be found for example in Lel et al. [12].

The droplet diameter and droplet impact velocity were determined out of the shadow images immediately prior to the impact. Therefore, an image analysis program written in MATLAB is used. After several post processing steps the droplet diameter and velocity are calculated from consecutive images.

**Results and Discussion**

We performed one- and two-component experiments using Castrol Hyspin AWS 10 and n-Hexadecane. The physical properties of these two liquids are summarized in Table 1. The resulting two-component systems are investigated to gain information about the impact morphology and evolution as well as the splashing/deposition limit. The origin system consists of a hyspin droplet impacting onto a hexadecane wall-film and the reverse system consists of a hexadecane droplet impacting on a hyspin wall-film. A systematic investigation was carried out for a wide range of experimental conditions: $0.1 < \delta < 0.5$, $300 < We_d < 1700$, $0.013 < Oh_d < 0.060$, $0.030 < Oh_f < 0.204$. In practice, only one droplet diameter was used and the thickness of the wall-film was varied to achieve different values of non-dimensional film thickness $\delta$.

For every thickness $\delta$ the Weber number $We_d$ was changed by varying the droplets fall height. To gain a deepened understanding of the impact morphology and evolution, related one-component experiments employing hyspin and hexadecane were performed. These experiments were conducted for $\delta = 0.1$ and $We \approx 1020$.

The current section is structured as follows. First, we perform a comparative study between the impact morphologies of the two-component systems for high Weber numbers of $We \approx 1020$ and $\delta = 0.1$. In a second step we extend this comparison by related one-component impact morphologies of hyspin and hexadecane. Since the droplet impact is symmetric (see [8]), only one view of the two-perspective images is presented in the following. Particular emphasis is given to the influence of the wall-film on the morphology of the splash. Hereafter, we present the results of the investigation of the splashing/deposition transition region for both two-component systems and establish an empirical correlation describing the splashing/deposition limit.

### Morphology of Two-Component Systems

The interaction of a hyspin droplet ($D_0 = 2.580 \, \text{mm}$, $v = 3.580 \, \text{m/s}$) with a thin hexadecane wall-film ($h = 0.260 \, \text{mm}$) is depicted in the first column of Figure 2. During the advancing phase the evolution of a cylindrical crown, fingers and secondary droplets proceeds as already described by Cossali et al. [1] for one-component droplet wall-film interaction. This is confirmed by comparing the evolution processes in Figure 2 with the one-component splashing of hexadecane in the first column of Figure 3. After reaching its maximum height at $T = 7.8$ holes appear at random locations in the crown wall. We assume that the formation of holes is triggered by local concentration gradients inside the crown wall. This assumption is plausible, since the duration of the impact process is too short for the development of a homogeneous liquid mixture in the crown. Furthermore, for the investigated one-component interactions of hyspin and hexadecane, as depicted in Figure 3, no hole formation is observed. The examined liquid combinations are characterized by a surface tension ratio close to one and viscosity ratio (droplet-to-film) of roughly five, respectively 0.2, (compare Table 1), hence the local rupture in the crown wall seems to be due to differences in shear stress rather than to surface tension gradients. During the receding of the crown the holes grow, probably due to the imbalance of surface tension along their rims. The contact line between crown and wall-film is shortened by holes (Fig. 2,

<table>
<thead>
<tr>
<th>Dynamic viscosity $\mu$ [Pa s]</th>
<th>Surface tension $\sigma$ [mN/m]</th>
<th>Density $\rho$ [kg/m$^3$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Castrol Hyspin AWS 10</td>
<td>0.0158</td>
<td>28.650</td>
</tr>
<tr>
<td>n-Hexadecane ($C_{16}H_{34}$)</td>
<td>0.0032</td>
<td>27.600</td>
</tr>
</tbody>
</table>

**Table 1.** Physical properties of hyspin and hexadecane.
Figure 2. Comparison between impact morphologies of hyspin/hexadecane ($W_e = 1015$ and $\delta = 0.1$) and hexadecane/hyspin ($W_e = 1027$ and $\delta = 0.1$) systems. The scale bar in the upper left corner measures 2 mm.

Figures 2 and 3. Impact morphologies of the two-component experiments for hyspin/hexadecane and hexadecane/hyspin systems. The columns show the evolution of the impact morphology for different times: T = 1.9, T = 5.1, T = 7.8, T = 10.3, and T = 12.3. The first column (col. 1) shows the outcome of the original system, and the second column (col. 2) shows the outcome of the reverse system.

Morphology of One-Component Systems

The one-component interaction of hexadecane ($D_0 = 2.550 \, \text{mm}$, $v = 3.810 \, \text{m/s}$, $h = 0.260 \, \text{mm}$) is shown in the first column of Figure 3. The impact outcome is splashing. During its ascending phase the crown has a convex shape (Fig. 3, col. 1, $T = 7.8$). Along the crown rim liquid fingers are formed and secondary droplets detach from the finger tips. The droplets are ejected upwards above the crown. After reaching its maximum height the crown rim starts to contract. The rim contraction is faster than the descending process of the crown. As a consequence the crown shape turns from convex to concave (Fig. 3, col. 1, $T = 12.3$). We assume that the contraction of the crown rim is due to the surface tension forces exceeding the viscous force. The surface tension forces try to shorten the crown rim to achieve a stable position while the viscous force maintains the crown shape. This is confirmed by the lamella shape of the high viscosity liquid hyspin, where no crown rim contraction can be observed. It can be seen in the second column of Figure 3, where the one-component interaction of hyspin ($D_0 = 2.700 \, \text{mm}$, $v = 3.510 \, \text{m/s}$, $h = 0.300 \, \text{mm}$) is depicted. In this case the impact energy, respectively the Weber num-

Effects of the wall-film and the viscosity

Since for both two-component experiments the Weber numbers and hence the kinetic energy of the droplets is similar ($W_{e,\text{origin}} = 1015$ and $W_{e,\text{reverse}} = 1027$), the effect of the wall-film, respectively of the viscosity, can be seen clearly. The shape of the crown turns with increasing viscosity from cylindrical to V-shaped, because the lower the viscosity of a liquid the more it can be pushed back by the impacting droplet. Additionally, the crown height is influenced by the viscosity. The crown height for the origin system is clearly higher than for the reverse system. This is most certainly due to the higher losses in kinetic energy induced by the wall-film with the higher viscosity, which is indirectly confirmed by the change of crown breakdown from rip off at the wall-film for low viscosity hexadecane wall-film to crown relapse for the high viscosity hyspin wall-film. Regarding the ejection height of the secondary droplets our assumption of energy loss due to higher viscosity is supported. Comparing the secondary droplet ejection for the two-component interactions at $T = 10.3$ in Figure 2, it can be seen that for the interaction with the low viscose wall-film hexadecane (col. 1) the secondary droplets are moving upward, while for the interaction with the high viscose wall-film hyspin (col. 2) the secondary droplets hover above the crown.
Figure 3. Comparison between impact morphologies of one-component interaction of hexadecane ($W_{ed} = 1035$ and $\delta = 0.1$) and hyspin ($W_{ed} = 1017$ and $\delta = 0.1$). The scale bar in the upper left corner measures 2 mm.

Hypin
Hexadecane

<table>
<thead>
<tr>
<th>T</th>
<th>Hexadecane</th>
<th>Hyspin</th>
</tr>
</thead>
<tbody>
<tr>
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<td><img src="image2.png" alt="Image" /></td>
</tr>
<tr>
<td>5.1</td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
</tr>
<tr>
<td>7.8</td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
</tr>
<tr>
<td>10.3</td>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
</tr>
<tr>
<td>12.3</td>
<td><img src="image9.png" alt="Image" /></td>
<td><img src="image10.png" alt="Image" /></td>
</tr>
</tbody>
</table>

Comparing the hexadecane/hyspin interaction with the one-component interactions yields similarities to both of them. The formation of fingers and secondary droplets is similar to the hexadecane/hexadecane interaction, but less distinct. The crown shape and height instead are similar to the shape of the lamella of the hyspin/hyspin interaction.

The major difference between one- and two-component impact morphology is the formation of holes in the crown wall. It only occurs for the two-component systems and it shortens the overall crown evolution process. This is confirmed by comparing the pictures for $T = 12.3$ in Figure 2 and 3. The lack of holes for one-component systems supports our above made assumption that concentration gradients are the cause of their formation. Since for both two-component interactions the crown shapes are similar to the crown shapes of the one-component interactions of the corresponding wall-film liquids, we assume that the wall-film properties (especially the viscosity) dominate the impact morphology.

### Splashing / Deposition Limit

The splashing/deposition limit for the hyspin-hexadecane permutations was determined by analysing manually the pictures of the impact sequence for each experiment. If the formation of secondary droplets at the fingertips of the crown was observed, the experiment was classified as splashing. Else wise, when no secondary droplets were formed, the experiment was classified as deposition. The experimental conditions span a wide range of $W_{ed}$,

The figures show the Weber number of the droplet $W_{ed}$ plotted against the dimensionless film thickness $\delta$. The blue diamonds mark the experiments classified as splashing and the red triangles mark the experiments classified as deposition in both figures.

Considering the results for the hyspin/hexadecane system presented in Figure 4, an increase in dimensionless film thickness $\delta$ leads to an increase in the critical Weber number $W_{ec}$ for the onset of splashing. For a dimensionless thickness between $0.4 < \delta < 0.5$ a sort of saturation exists. It seems that the wall-film thickness no longer has an influence on the impact outcome. Tropea and Marengo [13] assign this behaviour to the deep pool category, but in their classification the deep pool category starts at $\delta = 4$. For the verification of this saturation behaviour further experiments have to be conducted. Considering the results for
the hexadecane/hyspin system (Fig. 5) again an increase in wall-film thickness inhibits splashing, but no saturation effects are visible. As stated in the introduction, for one-component interactions the splashing/deposition limit is described by the $K$-factor. Since this is a common approach, we based our two-component splashing limit upon it. The energy for the formation of splashing originates from the kinetic energy of the droplet. Hence, we chose the Weber number of the droplet $We_d$ for the $K$-factor. For the two-component interaction we found that the wall-film properties have a major influence on the impact outcome, that is why we chose the alternative Ohnesorge number $Oh$ for the calculation of the $K$-factor. The alternative Ohnesorge number $Oh$, Eq. (5), employs the average viscosity of droplet and wall-film to take into account the influence of the wall-film liquid onto the impact outcome. And since the surface tension ratio of our liquid combination is close to one, the influence of surface tension on impact outcome is small compared to the viscosity influence and hence the droplets surface tension not an average value, is used for the calculation of $Oh$. Thus, the $K$-factor can be written as

$$K = We_d^{5/8} Oh^{-1/4}. \quad (9)$$

The empirical correlation describing the best fit for the splashing/deposition limit for the two hyspin-hexadecane systems reads as follows

$$K_C = 114 + 163 \delta^{6/5}. \quad (10)$$

The functionality of the correlation is chosen according to the previous dimensional estimate. For $\delta \rightarrow 0$ the behaviour certainly relates to the substrates surface roughness. In any case the correlation well matches the range $50 < K_C < 140$ given by Cossali et al. [1]. The application of the splashing/deposition correlation is shown in Figure 4 and 5. The black dashed line represents equation (10) converted into a function for the critical Weber number $We_c$, depending on the dimensionless film thickness $\delta$ and the alternative Ohnesorge number $Oh$. It can be clearly seen that values distinctly larger than $We_c$ result in splashing, while values lower than $We_c$ result in deposition.

**Conclusion**

The dilution of lubricating oil film in diesel engines necessitates the development of a model predicting the outcome of two-component droplet wall-film interactions. In this paper a morphology comparison between the two permutations of hyspin-hexadecane interactions is described. Due to the choice of wall-film liquid the splash morphology,
respectively the crown shape and maximum crown height, are strongly influenced. For low viscosity wall-films the crown shape is cylindrical, while for high viscosity wall-films the crown shape turns to conical. The maximum crown height decreases with increasing viscosity. For the two-component interactions the formation of holes in the crown wall is observed. The holes shorten the impact process. We attribute these effects to the lack of time for the liquids to form a homogeneous mixture. Consequently, the non-uniform distribution of shear stress induces ruptures in the crown. Since the surface tension ratio of the test liquids is close to one, the viscosity difference is the influencing parameter. These findings are confirmed by the results of the related one-component interactions of hyspin and hexadecane.

An empirical correlation for the splashing/deposition limit was established in the form of:

\[ W_{e_d}^{5/8} \tilde{Oh}^{-1/4} = 114 + 163 \delta^{6/5} \]

To verify if the presented approach for the splashing/deposition limit is negotiable to further two-component systems, additional experimental studies are required.

**Nomenclature**

Latin symbols
- \( D \) diameter
- \( h \) wall-film thickness
- \( k \) K-factor
- \( l \) length
- \( Oh \) Ohnesorge number
- \( \tilde{Oh} \) alternative Ohnesorge number
- \( T \) dimensionless time
- \( t \) time
- \( v \) impact velocity
- \( We \) Weber number

Greek symbols
- \( \delta \) dimensionless film thickness
- \( \mu \) dynamic viscosity
- \( \rho \) density
- \( \sigma \) surface tension

Subscripts
- \( 0 \) primary droplet
- \( c \) critical
- \( d \) droplet
- \( f \) wall-film
- \( \mu \) viscous length scale

**Figure 5.** Impact behaviour of hexadecane droplets onto hyspin wall-film plotted with respect to the Weber number \( W_{e_d} \) and dimensionless film thickness \( \delta \). Blue diamonds correspond to splashing behaviour and red triangles to deposition behaviour. The dashed line represents the splashing/deposition limit \( K_c \) (Eq. 10).
References


