Contact angle measurements for automotive exterior water management

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Abstract

The simulation of fluid flow over solid surfaces is important in many applications, for example, in automotive applications where good visibility and the performance of external sensors are essential. Multiphase CFD simulation methods such as level set or coupled level set–volume of fluid typically require a validated dynamic contact angle model as a function of capillary number to accurately resolve the near wall behaviour. This paper explores an experimental approach to identify a suitable contact angle model for pure and contaminated water on glass and painted surfaces. Applying image processing methods to high-resolution digital images of droplets descending flat plate samples of the required surfaces, the dynamic advancing and receding contact angles and capillary number are determined. Cox–Voinov, de Gennes and Yokoi models are parameterised from the experimental data, and the Yokoi model is shown to be the most suited to these surface/fluid combinations where hysteresis is significant. A multiphase simulation implementing the Yokoi model demonstrates good correlation for the Bond number between simulation and experiment.

Graphic abstract

1 Introduction

Automotive manufacturers are under pressure to reduce the cost of vehicle development by reducing the time for a vehicle programme and cutting the number of prototypes. To this end, there is an increasing shift to virtual prototypes and testing using CAE tools such as CFD. To truly realise the benefits of such developments, the simulations must be validated with well-characterised experiments using measured variables and parameters. The CAE tool can then be used to identify and test small design improvements that ultimately improve customer satisfaction and safety.

Exterior water management (EWM), in the automotive industry, is the study and management of surface water on the car. Hagemeyer suggests three sources of contamination

(Hagemeyer et al. 2011). Primary contamination relates to rain impacting the vehicle; foreign contamination is the result of spray from other vehicles; and self-contamination is the result of spray created by the vehicle itself. In all three scenarios, the surface flow begins as droplets deposited on the surface that may coalesce with other droplets to form large droplets and ultimately rivulets and thin films.

The presence of surface water and contaminants affects visibility, for example, side glass (Spruss et al. 2013; Landwehr et al. 2017), rear glass and windscreens, and with the increasing application of advanced driver-assistance systems (ADAS), it can also affect cameras and other sensors. In addition, poorly managed drips from opening doors or tailgates or the transfer of contaminants to drivers and passengers can negatively impact satisfaction. Channels for controlling water flow can be effective but must be included at an early stage of the design and must not detract from the vehicle appearance or increase drag. The ability to perform

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accurate simulations at an early stage of the design is therefore paramount.

Experimental work on water management for the heating, ventilation and air conditioning (HVAC) cowl located between the trailing edge of the bonnet (or hood) and the windscreen was studied by Aroussi et al. (2005). The cowl should enable air to be drawn into the HVAC system without entraining fluid. As such, ensuring that water is appropriately managed is absolutely fundamental. Aroussi's experiments studied the flow of water over a bonnet at different speeds and vehicle inclination angles to understand what may cause fluid to enter the cowl. The approach used cameras to record fluid position with a sufficient frame rate to calculate the velocities of the rivulets. While this is a simple approach, it generates some useful quantitative data; however, no effort was made to characterise the fluid–surface interaction that would enable comparable numeric simulation.

Landwehr et al. (2016) conducted an investigation into visibility through wetted glass. Two glass types were tested, taken from the windscreen and side and rear screens, from fifteen different vehicles. The glass was held in a horizontal orientation and two droplets formed and imaged on each glass sample. The contact angle was identified by assuming

the profile was part of a sphere and relating the measurable height and radius to the contact angle. Static contact angles in the range $30 < \theta_s < 75^\circ$ were identified for the side and rear screens with a calculated average of approximately 50° , whereas the range for the windscreen was $10 < \theta_s < 55^\circ$ but no data were provided to calculate an average value in this case. It is hypothesised that the windscreen has a smaller contact angle because the glass was a used sample, and the abrasive effects of the screen wiping action had affected the surface the abrasive nature of the screen wiping action. It is noted that with only two droplet measurements per sample, there is likely to be significant experimental uncertainty. Figure 1a shows an example of static droplets; one is hydrophilic, and one is hydrophobic. Figure 1b shows an example of a dynamic droplet moving down a tilted plate.

Spruss et al. (2013) studied water flow experimentally on both the windscreen and side windows. Water, doped with UV dye and illuminated with a UV lamp, was sprayed towards the windscreen during a wind tunnel test. The wipers were used, and their effect on flow over the side glass was recorded with a video camera. The results could provide a useful qualitative validation for numeric simulation, but without specific contact angle data for the tested

Fig. 1 Droplet characteristics

surfaces and fluids, a rigorous comparison with simulation would be difficult.

There are a number of approaches to numerically simulating surface flow. Thin film techniques (Karbon and Longman 1998; Kruse and Chen 2007; Jilesen et al. 2015; Dasarathan et al. 2016; Jilesen et al. 2018, 2019) have been used for simulation of A-pillar overflow, side window flow and windscreen flow, but the limitations of the approach are identified by both Jilesen et al. (2018) and by Dianat et al. (2017a). These include the lack of modelling of partial wetting, a lack of a model for velocities normal to the surface and no physical process to simulate phenomenon such as stripping. The first issue is of particular importance in the case when fluid tends to follow the path of a previous droplet in physical experiments, whereas the second is of greater importance if the fluid has to traverse channels or lips and the final is that fluid stripping processes are an important phenomenon in many aspects of automotive exterior water management. Another method is the simulation at a molecular level of fluids (Shikhmurzaev 1993; Shikhmurzaev and Sprittles 2013; Sprittles and Shikhmurzaev 2013; Sibley et al. 2015). This method, while promising as a means to accurately simulate the physics, is currently unsuitable for EWM simulations due to the high processing requirements.

Both volume of fluid (VOF) and level set (LS) methods can be employed for EWM, but while VOF conserves mass, it does not smoothly represent the interface between phases, and LS represents the interface well but does not conserve mass. A coupled approach such as that employed by Dianat et al. (2017a, b); Afkhami et al. (2009) combines the advantages of the two methods, albeit at an additional computational cost. Dianat et al. (2017b) performed both computational and experimental works, studying the flow of a rivulet breaching a water management channel. The test case constituted a painted surface tilted at an angle with a rivulet formed near the top of the surface. A high speed camera was aligned to a water management channel oriented perpendicular to the flow direction. The rivulet was analysed for position and height at key locations as a function of time and compared to numerical simulation. It is shown that the coupled level set–volume of fluid method is appropriate for EWM problems, but it is concluded that to match simulation results fully to experimental data, there is a need for a high-quality experimentally based model for dynamic contact angle. The simulations include one case with the rivulet purely driven by gravity and two air co-flow cases, all based on the same contact angle model. The least computationally expensive variant relies on a contact angle model matched to the scale of the mesh (Dianat et al. 2017a). This is typically achieved with a model that is a function of the capillary number. The capillary number, Ca , relates viscous and surface tension forces through the fluid viscosity μ , the

velocity of the gas–liquid interface at the contact line U and the surface tension σ :

$$Ca = \frac{\mu U}{\sigma} \quad (1)$$

1.1 Typical contact angle models

A number of contact angle models exist and have been compared in various works (Puthenveetil et al. 2013; Le Grand et al. 2005). The Cox–Voinov model (Cox 1986; Voinov 1976) defines the dynamic contact angle, θ_d , as a cubic function:

$$\theta_d^3 - \theta_s^3 = \Omega_1 Ca \quad (2)$$

where θ_s is the static contact angle and Ω_1 is a constant.

The de Gennes model (de Gennes 1986) also defines the dynamic contact angle as a cubic function but in a more complicated fashion:

$$\theta_d(\theta_d^2 - \theta_s^2) = K Ca \quad (3)$$

where K is a constant.

Tanner (1979) postulated that the capillary number was again a cubic function:

$$Ca = k(\theta_d - \theta_s)^3 \quad (4)$$

where k is a constant. Yokoi proposed that when inertia is the dominant force, there were a maximum dynamic advancing contact angle, θ_{mda} , and a minimum dynamic receding contact angle, θ_{mdr} , along with a different material constant dependent on the motion: k_a for the advancing contact angle and k_r for the receding contact angle. This is shown in Eq. 5.

$$\theta_d = \begin{cases} \theta_{mda} & \text{if } U_{CL} > 0, \\ \theta_{mdr} & \text{if } U_{CL} < 0, \end{cases} \quad (5)$$

where U_{CL} is the velocity of the contact line. Combining Eqs. 4 and 5 results in Yokoi's formulation (Eq. 6):

$$\theta_d = \begin{cases} \min \left[\theta_s + \left(\frac{Ca}{k_a} \right)^{1/3}, \theta_{mda} \right] & \text{if } U_{CL} \geq 0, \\ \max \left[\theta_s + \left(\frac{Ca}{k_r} \right)^{1/3}, \theta_{mdr} \right] & \text{if } U_{CL} < 0, \end{cases} \quad (6)$$

All of these models require experimentally measured contact angle data to determine the coefficients.

1.2 Measurement techniques

There are many approaches to measuring the contact angle, including imaging of drops, the Wilhelmy plate method and the tilting plate method. Numerous works compare in

detail the differences and benefits of the methods (Yuan and Lee 2013; Li et al. 1992; Srinivasan et al. 2011) so that is not repeated here. The work by Kwok and Neumann (1999), Korhonen et al. (2013), Vuckovac et al. (2019) and Huhtamäki et al. (2018) uses a flat surface and fit curves to an axisymmetric drop using known physical models. The work here requires the generation of data suitable for simulation of moving drops. As such, a method of identifying the dynamic contact angle is required, and as recognised by Huhtamäki et al. (2018), the axisymmetric drop approach is not suitable. Šikalo et al. (2005a) and Šikalo et al. (2005b) study the spread factor and contact angle of a droplet impacting a surface with rear illumination. The results for water on glass go up to relatively high capillary numbers for automotive EWM ($> 4 \text{ m s}^{-1}$) and do not include any negative capillary numbers. Issues around the effect of aerodynamic effects on the contact angles are also mentioned. The method chosen for the work presented here is to place droplets on a surface and image them with a backlight. This approach will work for all surface and fluid combinations and is relatively quick to perform making a large number of measurements practicable. Collection of sufficient data will ensure that measurements affected by surface imperfections will not disproportionately skew the final result; the final fitted model should not be unduly effected by one measurement. The latter is important because the surfaces to be examined are not typical of those usually found in work reported in the literature where the surface is generally highly uniform. Indeed, Demel et al. (2019) note that no two tests of surface flows on automotive surfaces will generate the same result. In this work, an aluminium plate painted to an automotive finish is employed that has surface imperfections. Yuan and Lee (2013) and Eral et al. (2013) both note that such imperfections result in contact angle hysteresis. Dussan (1979) defines contact angle hysteresis:

...for many material systems there exists an interval $[\theta_R, \theta_A]$, with the property that if θ lies within this interval then the contact line does not appear to move.

Furthermore, such imperfections will create pinning events (Tsoumpas et al. 2014). If measurements are made during a pinning event, then they will not be in an equilibrium state as is assumed for analysis. This will manifest itself in variations in both velocity (capillary number) and contact angle. As such, it is to be expected that there will be a variation in the data not normally associated with these tests. The potential for variation in the data is further exacerbated by the deliberate addition of contaminant material in the second part of this work.

Puthenveetil et al. (2013) conducted a series of tests using water on fluoroalkyl silane (FAS)-treated glass and mercury on glass. For water, this involved creating a droplet of water on the surface via a syringe and allowing the droplet

to run down the surface. Images were taken from the top and side with illumination provided behind both cameras, respectively. For safety reasons, the mercury was tested on the internal surface of a glass roller, again imaged from the side and above with illumination from behind. The imaging from above allows for capture of the droplet shape and comparison to the cusping analysis (that is the angle of the droplet tail when viewed from above) presented by Le Grand et al. (2005).

1.3 Aims

This work aims to:

1. Conduct robust, reliable experiments that will realise a large volume of useful data for practical automotive surfaces
2. Identify suitable models and their parameters from experimental data
3. Generate initial validation data for CFD simulations of pure and contaminated water in an automotive application.

The remainder of the paper is split into three parts, a description of the experimental methodology, a study of de-ionised water on a typical painted aluminium surface with a review of models and simulation capabilities and finally the results from both de-ionised and contaminated water on clean and treated glass.

2 Methodology

The purpose built rig, shown in Fig. 2, allowed different surfaces to be mounted within a tilting mechanism that can be set at any angle and thereby generate different droplet speeds. A frame (shown schematically in Fig. 2a and the vertical extrude shown in Fig. 2b) ensures that the rig remains grounded during the tests and allows a tilting frame to rotate along an axis. This tilting frame supports the surface of interest and has mounting brackets to hold a Digital Single Lens Reflex (DSLR) camera on one side and a strobe on the other (as shown in Fig. 2a). To ensure controlled exposures whereby the only light source was the strobe, a cover was added to block out ambient light (Fig. 2b).

The combination of a high-resolution Nikon D5200 DSLR (6000 × 4000 pixel APS-C sensor) and Sigma 180 mm macro-lens resulted in a typical spatial resolution of 175 pixels per mm. This is comparable to the cell size used in Dianat et al. (2017a) of 74 μm .

The strobe, an Elmred-Turbo-800, was adjusted to provide a flash of 4.31 μs duration at either 3 Hz or 8 Hz depending on the speed of the droplet on the surface. A diffusing

Fig. 2 Experimental rig showing test region and optical arrangement

(a) Schematic showing side and normal view of arrangement

(b) Lighting cover over test section

material and red filter were located in front of the strobe to reduce spatial intensity variations and allow filtering in post-processing, respectively. The latter ensures a sharp shadow image when just the green channel is selected. A single camera exposure of 1 s was taken per test, yielding an effective multiple exposure image for analysis. An example image taken with the strobe operating at 3 Hz can be seen in Fig. 3 with key features highlighted. The camera and light source were not synchronised, so the lighting could be different one image to the next. As such, a background image subtraction typically employed to enhance an image prior to processing was not available for use.

Droplets were manually produced from a syringe onto the level test surface. While using this approach the volume of fluid produced can vary by up to 2 μL (Hodgson et al. 2018) from test to test, target volumes were used to provide consistency between tests. This variation will result in a droplet of slightly different geometries and likely result in a different velocity. However, both actual geometry and velocity are identified from the image and are used in the analysis; the volume tested is utilised only to group results and determine whether any dependency on volume exists. Creating the droplet on a level plate rather than a tilted plate allows the study of larger droplets because they do not breakup while being

Fig. 3 Black and white conversion using a green filter of an example droplet

created. Once the droplet has been deposited, the test surface was then raised to the required angle and an image captured once the droplet entered the camera's field of view. As such, these droplets are only driven by gravity and not by aerodynamics. After each test, the surface was dried with a microfibre cloth until there were no visible indicators of the previous test. This approach to cleaning the test surface is much simpler than other work that uses a combination of chemicals and heat to ensure consistency. Given the specific aim of these experiments, it was felt that variations at the sub-macroscopic level were not only acceptable but also useful in understanding the variation that may occur; it is therefore not expected that these experiments will be highly repeatable on a test-by-test basis. However, variations due to the wetted nature of the surface should be minimised. As such, the amount of drying required was sufficient that condensing warm damp air on the surface immediately after a test did not reveal any indications of the previous droplet. Using the approach, described droplets were tested on the painted aluminium surface in a speed range of $0.0020 < U < 0.0527 \text{ m s}^{-1}$ by tilting the plate between 20° and 35° .

Three different surfaces were tested: plate aluminium machined, painted and finished to an automotive finish, untreated glass and glass treated with a commercially available hydrophobic coating. The surfaces were characterised using a Bruker NPFlex 3D Surface Metrology white light interferometer. This is a non-contact measuring device with a typical repeatability of 0.1 nm. Samples taken here had a surface area of approximately 0.012 mm^2 with a planar spatial resolution of 200 nm per pixel. Three measurements of every surface from within the test regions were taken and combined to give typical surface roughness values, shown in Table 1, where R_a is the surface roughness in nm. The aluminium is an order of magnitude higher than the glass, with the treated glass being somewhere between.

The surfaces were tested with pure de-ionised water (referred to as water) and water heavily saturated with sodium chloride (referred to as saltwater). Salt was used to contaminate the water for two reasons; firstly, it dissolves in the water and hence changes the properties sufficiently to be of interest, and secondly, because it is relatively representative of water, that may be on the surface of a car during cold weather.

To identify the density, viscosity and surface tension, the molarity, M , of the solution is required. 16.8 g of salt (NaCl) was fully dissolved in de-ionised water. This resulted in 0.2875 mol and hence a molarity, M , of 5.74. Zhang and Han (1996)

Table 1 Measured surface properties

Surface	R_a (nm)
Painted aluminium	34.17
Glass	3.29
Treated glass	12.07

tabulate some key data of salt solutions at varying molarities, including viscosity and density. These are reproduced here graphically in Fig. 4. The red and blue horizontal lines relate to the tested molarity with a resulting density of 1187 kg m^{-3} and viscosity 1.693 mPa s .

The surface tension of the saltwater mix can be calculated using the equation detailed in Kaye and Laby (2015).

$$\sigma_{\text{Soln}} = \sigma_{\text{H}_2\text{O}} + M \cdot \Delta\sigma_{\text{NaCl}} \quad (7)$$

Key values for the fluid properties of both water and saltwater are given in Table 2. The addition of salt to the water increased the density by 18 %, viscosity by 69 % and the surface tension by 12 %. Although the level of contamination may be considered extreme, these changes in fluid properties strongly suggest that using standard values for water, and the associated contact angle models, for performing real-world surface flow simulations will generate potentially unrepresentative results.

Water has a tendency to leave a thin trail behind it, with associated contact line identification issues as described by Srinivasan et al. (2011). The receding contact line may therefore be pinned somewhat behind the main body of the droplet making it unfeasible to capture both advancing and receding contact lines in the same image. Furthermore, the height of the thin film that is formed by such a tail is

Fig. 4 Viscosity and density of saltwater for different molarities

Table 2 Fluid properties for water and saltwater

Parameters at 25°	Water	Saltwater
Surface tension, σ , (N m^{-1})	0.072	0.0814
Dynamic viscosity, μ , (mPa s)	1.002	1.693
Density, ρ , (kg m^{-3})	1000.0	1187

Fig. 5 Example imagery from processing. **a** Green channel with markers indicating identified ACL (red +), advancing interface angles (red), receding interface angle (green) and heights (blue), **b** Example image showing receding contact line region with lines at 0.1 mm and 0.2 mm

less than 0.1 mm. Figure 5b shows an example of water on painted aluminium with lines showing heights of 0.1 mm (blue) and 0.2 mm (green).

Close examination shows that the interface angle at the blue line at 0.1 mm is very low. The interface angle from this point to the receding contact line is therefore very low. At 0.2 mm, the interface angle is significantly higher. These heights from the surface equate to 1.5–3 cells based on Dianat et al. (2017a). The contact angle is applied as a boundary condition in a simulation by fixing the angle of the interface in the near wall cell. Therefore, it is this ‘apparent contact angle’ at a fixed distance from the wall that must be specified by the model. The experimental data therefore need to be matched in spatial resolution if the simulation is to accurately capture the geometric features, and hence the associated motion of the droplet. In practice, if, as here, the experimental data are captured 0.2 mm from the wall, the near wall grid resolution should have a similar spatial resolution.

A formal pixel intensity interpolation, for example, as often used in PIV, was initially attempted to identify the edge of the droplets. This showed some success with the initial fluid–surface combination. However, the variations in illumination combined with the effective multiple exposure technique meant that the process was too inconsistent for all combinations. As such, a similar approach was conducted using manual methods. All the image data are processed with MATLAB code written in-house. For every droplet in every image, the software shows the region around the contact lines (both advancing and receding) as shown in Fig. 5b. The operator then checks and adjusts the advancing contact line—shown by red crosses in Fig. 5a—interface angle—shown by the red or green lines—and the maximum height—shown by the vertical blue lines. The selected points are not limited to pixel resolution due to the manner in which

MATLAB displays the images. The velocity is calculated as the difference in ACL position multiplied by the strobe frequency.

The errors from manual identification of the interface at the different heights can be quantified by considering perturbation of the selected points. An example droplet with a receding contact angle of $\theta_{dr} = 7.0^\circ$ and an advancing one of $\theta_{da} = 52.9^\circ$ was selected to study. The angles identified at 0.2 mm are derived from the manually selected interface points having a difference in position in the image of $\delta x_r = 144$, $\delta y_r = 17.6$ and $\delta x_a = 7.9$, $\delta y_a = 9.1$, where $\tan \theta_d = \delta y / \delta x$ (distances all in pixels). If an error value is considered for each direction, ϵ , then $\tan \theta_d = (\delta y + \epsilon_y) / (\delta x + \epsilon_x)$. It is reasonable to assume that the operator can select the interface within 2 pixels, especially since the selection points are sub-pixel in size. As such $-2 \leq \epsilon \leq 2$ pixels, then the contour plots shown in Fig. 6a, b can be formed.

The higher curvature of the advancing side makes it more susceptible to variation in the selected tangent, up to several degrees in the worst case scenario. Conversely, the error in the shallower receding contact angle is typically less than 0.5° . This is as expected; a shallow angle with a low rate of change as found in receding angles (as shown by the green line on the right-hand side of the image in Fig. 5a) will be far less prone to selection error than an angle with a higher rate of change, as found in advancing contact angles.

3 Results for water on aluminium

Figure 7 shows the contact angles identified at 0.2 mm from the surface plotted against the capillary number for water on a painted aluminium surface. The different droplet sizes are represented by different symbols. The receding contact angles show a good level of repeatability with

Fig. 6 Perturbation in pixels of selection point on **a** advancing contact angles and **b** receding contact angles. Note different scales

a clear asymptote around 7° . The larger droplets generally produce the largest capillary numbers (velocity) as expected. The advancing contact angles have a larger level of variance, especially the smaller drops where $0 < Ca < 0.2 \times 10^{-3}$. The experimental methodology used to obtain the capillary number inherently results in relatively low error on position data, but this must be differentiated to obtain a velocity, increasing the noise. As previously discussed and noted by Demel et al. (2019), the nature of the surface, with local small imperfections, will result in more variance as small-scale pinning effects impact on both the capillary number and contact angle identification. The hysteresis discussed by (Tropea et al. 2018) is clearly present.

Fitting a Cox–Voinov model in its standard form (Eq. 2) is not practical here because it does not account for hysteresis. The addition of a second parameter to separate advancing and receding contact angles, $Ca > 0$, is feasible (Eq. 8)

$$\theta_d = \begin{cases} (\theta_s^3 + \Omega_1 Ca)^{1/3} & \text{if } Ca \geq 0, \\ (\theta_s^3 + \Omega_2 Ca)^{1/3} & \text{if } Ca < 0. \end{cases} \quad (8)$$

While the advancing contact angle fit improves under this modification, the receding contact angle cannot be represented because the model has no scope for the significant hysteresis when static; that is, the model assumes that $\theta = \theta_s$ when $Ca = 0$.

Adding a third parameter to allow for hysteresis yields Eq. 9.

$$\theta_d = \begin{cases} (\theta_s^3 + \Omega_1 Ca)^{1/3} & \text{if } Ca \geq 0, \\ \kappa + (\theta_s^3 + \Omega_2 Ca)^{1/3} & \text{if } Ca < 0. \end{cases} \quad (9)$$

The effect of the hysteresis parameter, κ , is clearly shown in Fig. 7. This produces a good fit (confirmed by the R^2 value in Table 3).

The fit for the de Gennes model has similar issues to the Cox–Voinov model; namely, the advancing contact angle shows reasonable levels of fit, but the receding contact angle does not.

Fitting Yokoi's model to the data, as shown in Fig. 8, results in a good fit for both advancing and receding contact angles. The data show that no asymptote is identified for the advancing model.

Table 3 shows the fit suitability for the models reviewed. The objective measurements confirm what is observed in Figs. 7 and 8. The negative r^2 value for the de Gennes model is a result of the format of the model (lack of a constant term) and indicates that the mean is a better fit than the fitted model (MathWorks (2018)). The Yokoi model will be fitted

Table 3 Goodness of fit for models applied to experimental data

Model	r^2
Cox–Voinov	0.3810
Cox–Voinov modified	0.2645
Cox–Voinov modified 2	0.8844
de Gennes	−0.8367
Yokoi	0.8970

Fig. 7 Experimental data for capillary number and contact angle with a three-parameter Cox–Voinov model fit

Fig. 8 Experimental data for capillary number and contact angle with a Yokoi model fit

to the data for the rest of this work, having previously been successfully demonstrated in relevant simulations Dianat et al. (2017a).

Past validation of simulations has been undertaken by comparing the geometry visually (subjectively) of a simulated drop or rivulet to an experimentally imaged one (Dianat et al. 2017a; Yokoi et al. 2009). Apart from the lack of objectivity in such an approach when it is known experimentally that there is variation in the behaviour and shape of each drop, the experiment reported in this paper is expected to generate variation because of the surfaces employed. So an objective comparison between simulation and experiment is proposed that considers the modified Bond number as a function of the contact angle. The simulation directly calculates a contact angle based on the droplet velocity through a model. The output from the simulation is the geometry, and it is this that should be compared to the experiment. This approach should result in greater confidence that simulated geometries are representative of experimental tests. The Bond number is defined as:

$$Bo = \frac{\rho g L^2}{\sigma} \quad (10)$$

The Bond number relates the body force to surface tension force, where ρ is the density of the fluid, g is acceleration due to gravity, and L is a characteristic length; in this work, the maximum height (h in Fig. 1b) of the droplet is chosen as the characteristic length for simplicity of measurement, whereas Puthenveetil chose the cube root of the droplet volume. The Bond number can be modified by multiplying by $\sin(\phi)$ giving

$$Bo_\phi = \frac{\rho g L^2}{\sigma} \times \sin(\phi) \quad (11)$$

where ϕ is the tilt angle of the surface. This modified Bond number allows for direct comparison of experimental and numeric simulation. The cusping analysis of Puthenveetil et al. (2013); Podgorski et al. (2001) would be a useful additional method for validation of numeric simulation. However, it is precluded from this work because of the aim to study a practical painted aluminium surface.

The advancing and receding contact angles as a function of modified Bond number are shown in Fig. 9, with the markers distinguishing the size of the droplet. Unsurprisingly, smaller droplets have lower contact angles at lower Bond numbers. It is also observed that there is not a difference in the contact angle trend as a function of drop size.

As the Bond number (based on height) increases, the advancing contact angles increase due to the inertia forces. The collapse of data and smaller variation (when compared to the capillary data shown in Fig. 8) is because the measurement of the height for use in the Bond number

Fig. 9 Advancing and receding contact angles as a function of modified Bond number, split by droplet size, for water on painted aluminium

is subject to much less noise than calculating capillary number that requires differentiation of the measured data to determine the velocity. Further, unlike the capillary number data that assume the velocity is constant between images, the Bond number is not prone to surface imperfections affecting the data. The range in the modified Bond number for a given droplet size is a useful test case for CFD simulations because droplets that have the same volume will have different geometries and different places on an imperfect surface.

To make a comparison with numerical methods, a series of simulations employing the CLSVOF method as described in Dianat et al. (2017a), for a number of droplets and using the Yokoi model from Fig. 8, were performed and resulted in Bond number data shown in Fig. 10. The experimental data are shown with solid blue circles and the simulated data with empty blue circles. The Bond number for the advancing contact angles fits well with the experimental data, implying that the simulation is accurately forming the geometry of the head of the droplet at various times through the simulation, despite the apparently large variation in advancing contact angle from the experiment. The receding contact angle is less well matched to the experimental data. This shows that the contact angle data produced by the method here can be applied in a practical EWM simulation.

Fig. 10 Advancing and receding contact angles as a function of modified Bond number for both experimental (solid circle) and simulation (circle outline) for water on painted aluminium

4 Results for water and contaminated water on glass and treated glass

The static, maximum advancing and minimum receding contact angles for water and saltwater on glass and treated glass are summarised in Table 4. These were all obtained with the same method as the dynamic contact angles and are the average of 20 droplets for each fluid–surface combination. Water has a smaller static contact angle on both surfaces compared to the saltwater. The values for water on treated glass are very similar to the mean value identified by Landwehr et al. (2016) for the side and rear screens. This difference clearly demonstrates that the hydrophobic spray is performing as expected. The calculated increase in surface tension explains the increase in the static contact angles for a given surface.

Figure 11 shows the contact angles as a function of capillary number for all four fluid–surface combinations. The largest capillary numbers are for the contaminated

fluid tests. The water on glass case has the smallest contact angle range, as expected given the static contact angles given in Table 4. Table 5 details the Yokoi parameters obtained from the curve fit routines.

Treating the glass with the hydrophobic spray has not changed the typical capillary numbers, but the advancing contact angles measured at those values are higher on average, although with more spread. The receding values are very similar at around 6° . The addition of salt has a far greater impact on the results than the use of a hydrophobic spray. For the glass case, the capillary numbers are slightly larger, but much more tightly grouped. Again the receding contact angles for both cases are very similar to the water cases at approximately $5 - 6^\circ$. In all four cases, the receding contact angles have a similar, low value, suggesting an asymptote has been reached. The contaminated water on treated glass has the highest observed capillary number and can be said to have reached a maximum advancing dynamic contact angle at approximately 120° .

Figure 12 shows the identified contact angles as a function of modified Bond number for all four fluid–surface combinations, with red points being fluid on glass, green being fluid on treated glass, filled circles are water, and pluses are saltwater.

The data taken at zero tilt angle have been removed to simplify visualisation. (They are all on the y -axis.) The larger Bond numbers are generated on the treated glass, and the saltwater tends to produce larger Bond numbers than the water. Similar to the water on aluminium test, the data collapse well providing an important resource for validation of simulation work. Close inspection appears to reveal that the modified Bond number is independent of the contamination on both surfaces. The treated glass tests seem to have a minimum around $Bo_\phi = 0.1 - 0.15$, whereas the glass has a minimum around $Bo_\phi = 0.025 - 0.05$. At the higher range of modified Bond number ($Bo_\phi > 0.3$), the trends tend to converge for both advancing and receding angles. It is hypothesised that the relationship between the contact angle and the modified Bond number is independent from the salinity of the solution for a given surface.

Table 4 Key angles for tested fluid and surface combinations

Measure- ment	Water on alumin- ium	Water on glass	Water on treated glass	Saltwater on glass	Saltwater on treated glass
$\theta_s (^\circ)$	57	16	50	75	74
$\theta_{mda} (^\circ)$	84	80	100	110	120
$\theta_{mdr} (^\circ)$	6	6	6	5	5

Table 5 Identified Yokoi parameters

Surface	Fluid	k_a	k_r
Glass	Water	1.33×10^{-5}	2.35×10^{-3}
Glass	Saltwater	0.914×10^{-3}	5.20×10^{-6}
Treated glass	Water	4.82×10^{-5}	1.55×10^{-5}
Treated glass	Saltwater	6.97×10^{-5}	1.80×10^{-5}

Fig. 11 Contact angles as a function of capillary number for different surfaces and fluids. From top left, clockwise: water on glass, saltwater on glass, saltwater on treated glass, water on treated glass. Angles are measured at 0.2 mm

5 Conclusions

A rig was designed to specifically test fluids on different surfaces capturing shadows through managed optical conditions. Water was initially tested on an aluminium plate finished with automotive paint. The images were processed to obtain Bond and capillary numbers along with advancing and receding contact angles. When the contact angles are plotted against the modified Bond numbers, the trend is shown to be independent of the droplet size, presenting an opportunity for comparison with simulation.

A Yokoi contact angle model was fitted to the capillary number data and used in a CLSVOF simulation that replicates the experiment with a droplet traversing a surface. Height data from the simulation were extracted and used to calculate the Bond number for direct comparison to experiments. The simulation data showed a good match with experimental results, especially for the advancing contact angle, suggesting that such a model is suitable to obtain the correct droplet geometry. The receding contact angles were not such a good match for shorter droplets. Cell refinement in this region may improve simulations; however, the CLSVOF simulation is already computationally intensive, so further work is required to understand the sensitivity of receding contact angles on simulations.

Fig. 12 Contact angles as a function of modified Bond number (height) for different surfaces and fluids. Angles are measured at 0.2 mm

The aluminium plate was replaced with glass and a series of tests conducted involving water and saltwater on both dry glass and dry glass treated with a commercially available hydrophobic spray. The results demonstrate that the water on dry glass is significantly different to the other cases. A vital implication is that contact angle models for water are not sufficient for simulating surface water flows for automotive cases since it does not accurately represent water typical to rain and spray. The identified contact angles are also plotted as a function of the modified Bond number, with an excellent collapse of the data. Although not suitable for simulation parameters, this datum demonstrates an excellent validation method.

Further research should aim to replicate water typically found on cars: rainwater, windscreen cleaning water (for both summer and winter cases) and spray. Variations may occur on a seasonal and geographic basis. This expanded range of fluids should be coupled with other typical automotive surfaces such as painted and unpainted plastic and rubber. The study of additional surfaces may also provide an opportunity to search for correlation between surface roughness measurements and contact angles.

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