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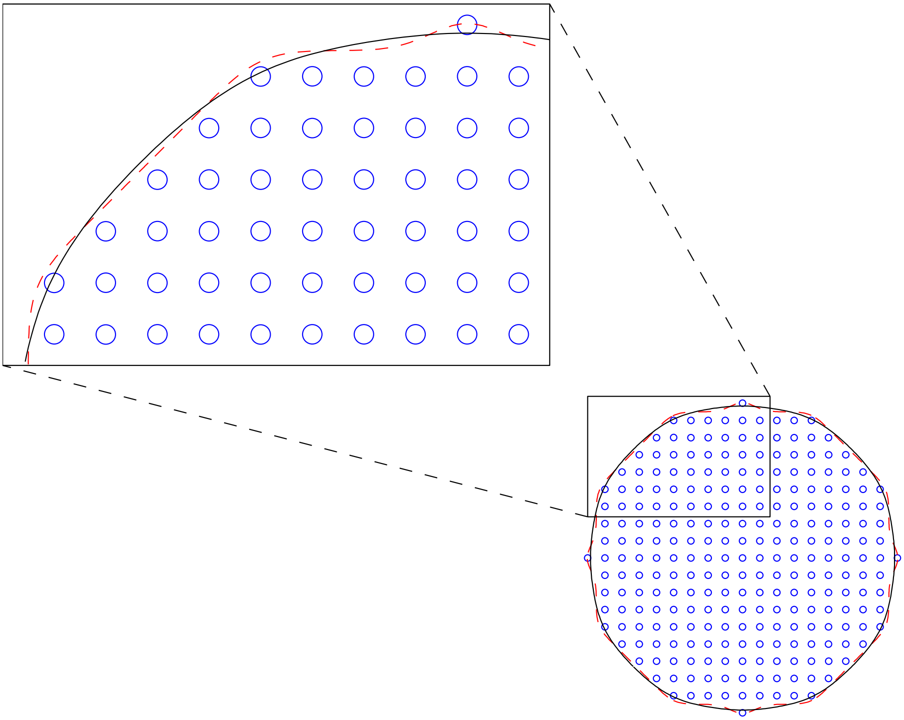

Droplet Breakup in Automotive Spray Painting

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Department of Applied Mechanics
Division of Fluid Dynamics
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2011

THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING
IN
THERMO AND FLUID DYNAMICS

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Cover:
Reconstruction of the interface between two fluids with the method described in Paper II. Red dashed line shows the original interface and the full black line the reconstructed smooth one.

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Droplet Breakup in Automotive Spray Painting

Thesis for the degree of Licentiate of Engineering in Thermo and Fluid Dynamics

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Abstract

Paint and surface treatment processes in a car paint shop are to a large extent automated and performed by robots. Having access to tools that incorporate the flexibility of robotic path planning with fast and efficient simulation of the processes is important to reduce the time required for introduction of new car models, reduce the environmental impact and increase the quality. The current version of the software for simulation of spray painting developed at the Fraunhofer-Chalmers Centre relies on measured droplet size distributions that can be used as input to the simulations. This thesis discusses techniques that can be used to simulate the droplet size distributions and therefore reduce the need for costly and complicated measurements.

Surface tension plays an important role during breakup as it acts to stabilize the droplets. On the small scales of droplets from 1-100 μm in diameter it is a strong force yet localized to the interface between the droplet and the surrounding medium. It is therefore crucial to have control over the interface and to this end a novel method for reconstructing the interface of the droplet is described. The method relies on approximation by Radial Basis Functions using a technique that enables the omission of small length scale structures in order to obtain a smooth representation that is suitable for numerical discretization.

Droplet size distributions have been simulated with the Taylor Analogy Breakup (TAB) model with promising results. A modification taking into account the large viscosity of the paint is introduced and the parameters of the model are tuned to the case of rotary bell spray painting commonly used in automotive industry. Results show that the model is able to capture the overall shape of the size distributions and that it captures the effect of the bell rotation speed, shifting the distributions toward larger or smaller droplets.

Keywords: spray painting, breakup, atomization, surface tension, computational fluid dynamics

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Björn Andersson
Göteborg, December 2011

LIST OF PAPERS

Paper I	R. Rundqvist, A. Mark, B. Andersson, A. Ålund, F. Edelvik, S. Tafuri, and J. Carlson. "Simulation of Spray Painting in Automotive Industry". *Numerical Mathematics and Advanced Applications 2009.* Ed. by G. Kreiss, P. Lötstedt, A. Målqvist, and M. Neytcheva. Springer Berlin Heidelberg, 2010, pp. 771–779. ISBN: 978-3-642-11795-4. URL: `http://dx.doi.org/10.1007/978-3-642-11795-4_83`
Paper II	B. Andersson, S. Jakobsson, A. Mark, F. Edelvik, and L. Davidson. "Modeling Surface Tension in SPH by Interface Reconstruction using Radial Basis Functions". *Proceedings of the* 5^{th} *International SPHERIC Workshop.* Ed. by B.D. Rogers. Manchester (U.K.), June 2010, pp. 7–14
Paper III	B. Andersson, S. Jakobsson, A. Mark, F. Edelvik, J. S. Carlson, V. Golovitchev, and L. Davidson. "Modified TAB Model for Viscous Fluids applied to Breakup in Rotary Bell Spray Painting". Report. Dec. 2011

Contents

Part I

Extended Summary

1 Introduction

Paint and surface treatment processes in the car paint shop are to a large extent automated and performed by robots. Having access to tools that incorporate the flexibility of robotic path planning with fast and efficient simulation of the processes is important to reduce the time required for introduction of new car models, reduce the environmental impact and increase the quality.

In automotive spray painting paint primer, color layers and clear coating are commonly applied through the Electrostatic Rotary Bell Sprayer (ERBS) technique. An image of an active bell is shown in Fig. 1.1. Paint is injected at the center of a rotating bell; the paint forms a film on the bottom side of the bell and is atomized at the edge. See Fig. 1.2 where the bottom side of a bell is shown where the painter enters in the middle and is forced towards the edge.

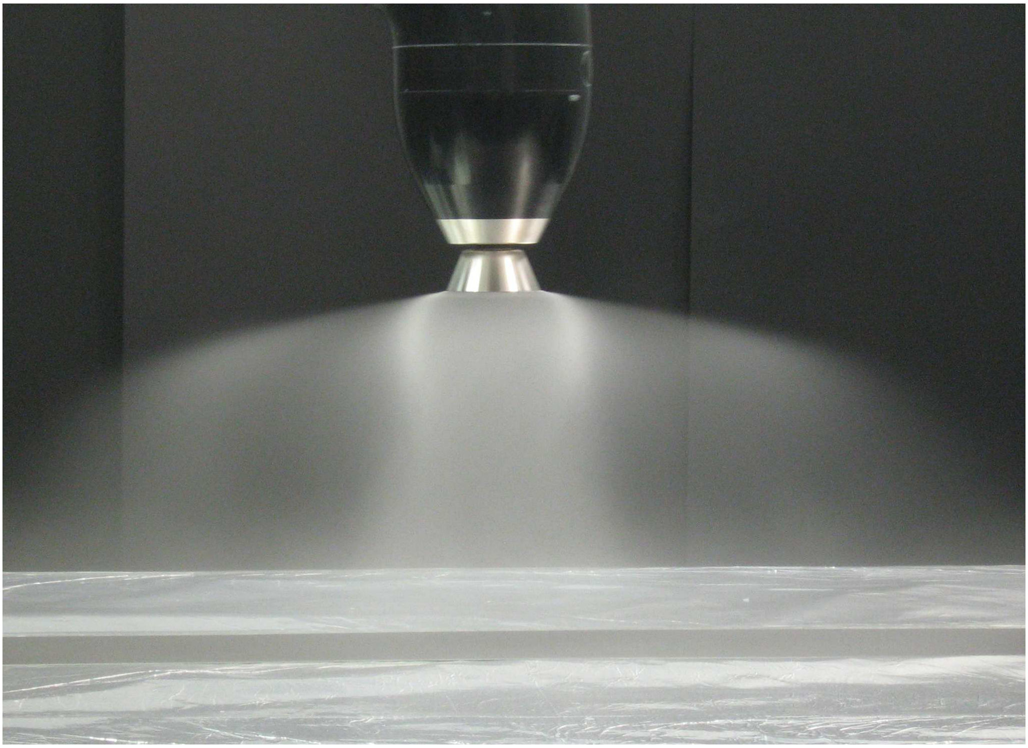

Figure 1.1: *Photograph of rotary bell spraying towards a target. The actual bell is the cone shaped part at the tip of the applicator head. Photograph courtesy of Swerea IVF.*

In the current version of the FCC software IPS Virtual Paint [4] the atomization step is not simulated but instead measurements of droplet size and velocity distributions close to the bell are required as input. These measurements are costly and requires special equipment to perform. In addition, creating initial conditions for the spray simulation

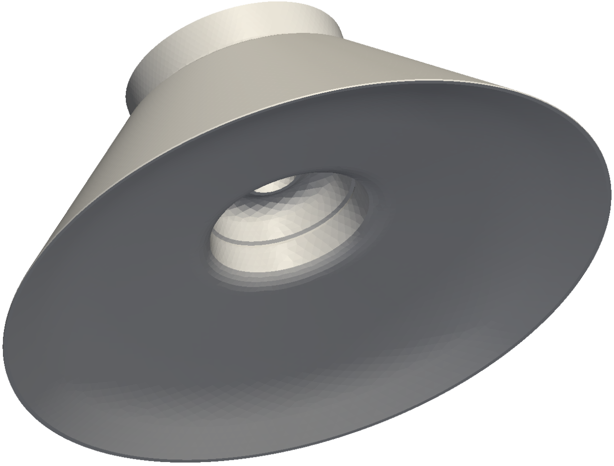

Figure 1.2: *Geometry of a bell, shown from below. The paint is injected in the middle and forms a film on the bottom side. The bell spins rapidly, with up to 50 000 revolutions per minute, and the paint is forced towards the edge where it enters the air and is atomized.*

involves some manual tuning of the parameters in the model to match the numerical solution to the measured fields.

The droplet size distribution in the spray determines its characteristics on how it reacts to the external forces applied by the air and the electrostatic field: large droplets tend to travel in straight lines and small droplets follow the force field closely. The behavior is characterized by the Stokes number that relates the response time of the particle to the timescale on which the field changes on. The particle response time is a function of its size, and also carried charge in the case of the electric field. The response time also scales differently for the fluid interaction and the electromagnetic one. It is therefore important to have good knowledge on the distribution of droplet sizes present in the spray in order to be able to perform spray painting simulations with high accuracy. If a better understanding on how the process parameters affect the distributions is gained it can be used in an optimization loop to tune the result of the painting to have a better visual appearance, be more cost effective, and to be more environmentally friendly.

2 Characterization of breakup

In order to reduce the costly and cumbersome size distribution measurements, the idea is to simulate the break-up of paint into droplets. By studying the region closest to the bell edge where the breakup is taking place we see that the atomization process can be characterized into two main components: Primary and secondary breakup. A snapshot of breaking paint is shown in Fig. 2.1 in which filaments of paint can be seen emanating from the edge of the bell. These filaments are formed by serrations at the bell edge that act as small channels for the paint, forcing it into the shape of evenly spaced fingers. The

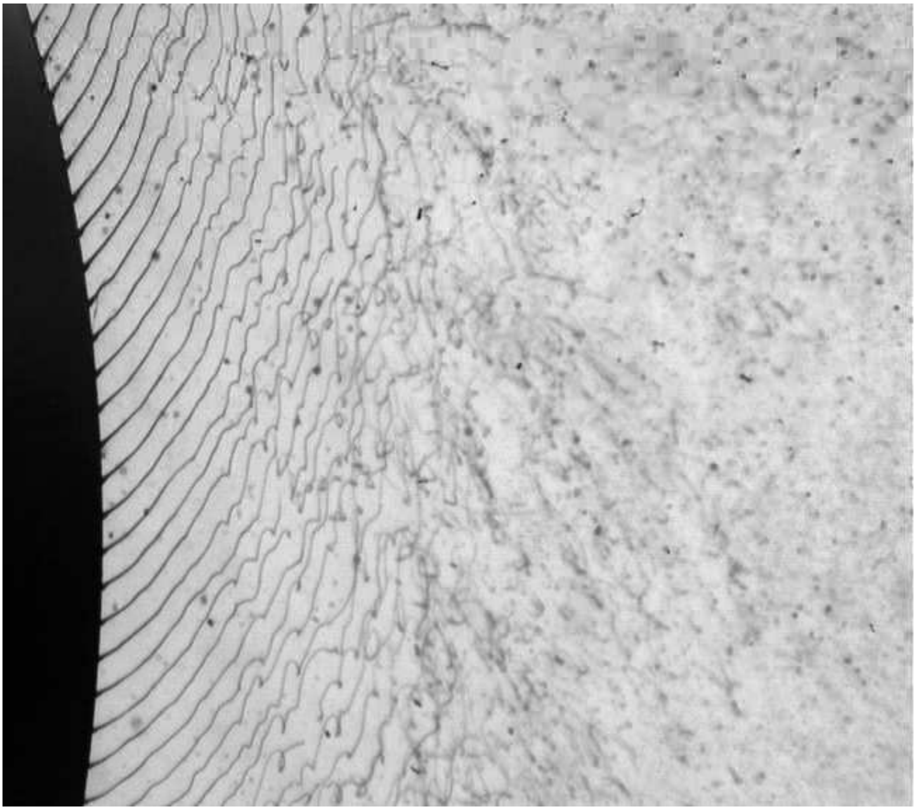

Figure 2.1: *Snapshot of paint breaking up. The bell edge is visible to the left and the paint enters the air as evenly spaced filaments. The bell spins giving the part of the edge shown a velocity directed downwards, creating the spiraling pattern of the filaments. After a few millimeters the filaments are distorted to the point where they break, forming non-spherical droplets breaking up further before forming stable droplets. Photograph courtesy of Swerea IVF.*

filaments are distorted by instabilities driven by the relative velocity to the air, and once the distortion is large enough, fragments break off. The fragments typically break further before reaching a stable size. This is called the secondary breakup.

2.1 Primary breakup

The primary breakup is not extensively treated in this thesis. In the third paper [3] the size distribution of the fragments of the primary breakup is modeled with a log-normal distribution with fragment sizes with mean and standard deviation equal to 100 and 50 μm, respectively. The speed of the fragments also needs modeling as it is reasonable to assume that at least some of the filaments relative velocity to the air is lost before splitting into fragments. In the paper the velocity of the fragments is modeled as a uniform distribution varying between the full tangential speed of the bell edge down to half of it. In other words, up to half the velocity is lost upon completion of the primary breakup, but only a minority of the fragments loose this much.

Experimental treatment of the primary breakup is of course difficult, as one cannot stop the fragments to undergo the secondary breakup. High speed imaging is however a possibility as shown in Fig. 2.1. By taking multiple such pictures with a small time separation it would be possible to estimate the speed of the filaments. The wavelength and development of the instabilities would also be possible to measure. Broken fragments might be possible to capture with the camera so that they could be measured, but this has proved to be difficult in practice.

2.2 Secondary breakup

The secondary breakup is targeted in the third paper [3] where the Taylor Analogy Breakup (TAB) model [5] is applied to the spray paint application. In the method droplets are modeled as harmonic oscillators, driven by the relative speed to the air. By adding coefficients to the expression for the drag force, restoring force, and the viscous force, the size distribution can be simulated by tuning the coefficients so that the results match the measurements. The TAB model does not, however, give much information about the qualitative breakup process as it is more complicated than what can be modeled by an harmonic oscillator. The reader is referred to *e.g.* [6] for an overview of the different breakup modes active in different regions of the phase space.

Experimental results for the secondary breakup are possible to extract, at least in the sense of the final result. The difficulty here is instead the initial conditions, that of course are the final results of the primary breakup. The secondary breakup is to some extent independent on the primary one, however, as droplets will continue to break until they are stable. It is probably reasonable to expect that second generation child droplets have lost the memory of the size and shape of the grand parent droplet. First generation child droplets may on the other hand have some heritage left, and the question that needs to be answered is how many generations of child droplets are produced on average.

3 Breakup modeling

Surface tension is important concept in breakup simulations as it is a stabilizing force acting on the droplet to prevent breakup. It acts on the interface of the droplet to the air with a magnitude that is proportional to the mean curvature of the interface,

$$\mathbf{F}_s = -\sigma \frac{\kappa_1 + \kappa_2}{2} \hat{\mathbf{n}}, \tag{3.1}$$

where σ is the surface tension coefficient, κ_1 and κ_2 are the two principal curvatures, and $\hat{\mathbf{n}}$ is the outward pointing normal of the interface. For a sphere the mean curvature is the inverse of its radius so that

$$\mathbf{F}_s = -\frac{\sigma}{R}\hat{\mathbf{n}}. \tag{3.2}$$

The force therefore grows as the radius of the droplet becomes smaller, and at some point it becomes the dominant force.

3.1 Surface tension discretization

If seen on an atomistic scale the surface tension acts on a thickness of a few atomic layers [7], but in practice with a realistic resolution the force can be seen to act on a two-dimensional manifold embedded in three dimensions. To overcome this problem and to convert it into a volume force acting in a narrow band, Brackbill *et al.* derived [8] the Continuum Surface Force (CSF) approach that enables the force to be applied to the neighboring cells to the interface in a computational code.

Even though the discretization of the force is converted to act as a localized volume force, stability problems can arise for smaller droplets because of the scaling shown in Eq. 3.2. The second paper [2] describes a new method to discretize the force that is in some sense independent of the grid that the Navier-Stokes equations is discretized on. In this way a smoother discretization is enabled that proved to increase the stability of the numerical simulations.

3.2 Stability criterion

The stability criterion can be expressed by the dimensionless Weber number,

$$We = 2\frac{\rho_g u_r^2 a}{\sigma}, \tag{3.3}$$

where ρ_g is the gaseous density, u_r is the modulus of the relative speed between the droplet and the surrounding air, a is the droplet radius, and σ is the surface tension coefficient. A larger Weber number implies a more unstable droplet, and the critical number above which breakup will occur (given enough time) can be determined from the empirical relation by Brodkey [9]

$$We_c = 12\left(1 + 1.077 Oh^{1.6}\right), \tag{3.4}$$

where the so-called Ohnesorge number, another dimensionless number, is evaluated as

$$Oh = \frac{\mu_l}{\sqrt{2\rho_l a\sigma}}, \tag{3.5}$$

where μ_l is the dynamic viscosity of the liquid. The Ohnesorge number is dependent solely on the droplet itself, whereas the Weber number also includes properties of the surrounding medium and the droplet's relative velocity to it. We see that the critical Weber number is approximately 12 for droplets with small Ohnesorge numbers, $\lesssim 10^{-1}$. For larger value it increases asymptotically as $Oh^{1.6}$. It is interesting to study the effect of the droplet diameter on the stability criterion. As it enters the Ohnesorge number in the denominator an increased stability is expected for smaller droplets. The transition where the stability start to depend on the droplet diameter depends on the other components of the Ohnesorge number; the viscosity, density and surface tension coefficient. In the case of solvent borne clear coat the properties are listed in Table 3.1 where we see that it is the viscosity that stands out the most compared to *e.g.* water. Figure 3.1 shows the critical Weber number as a function of droplet diameter for the paint material. It is not entirely clear, however, that the scaling is correct for large Ohnesorge numbers as the amount of experimental evidence for $Oh > 3$ is limited.

Property	Symbol	Value	Unit
Dynamic viscosity	μ	0.12	$Pa{\cdot}s$
Density	ρ	995	kg/m^3
Surface tension	σ	0.025[1]	N/m

Table 3.1: Parameters of the paint material studied: Solvent borne clear coat.

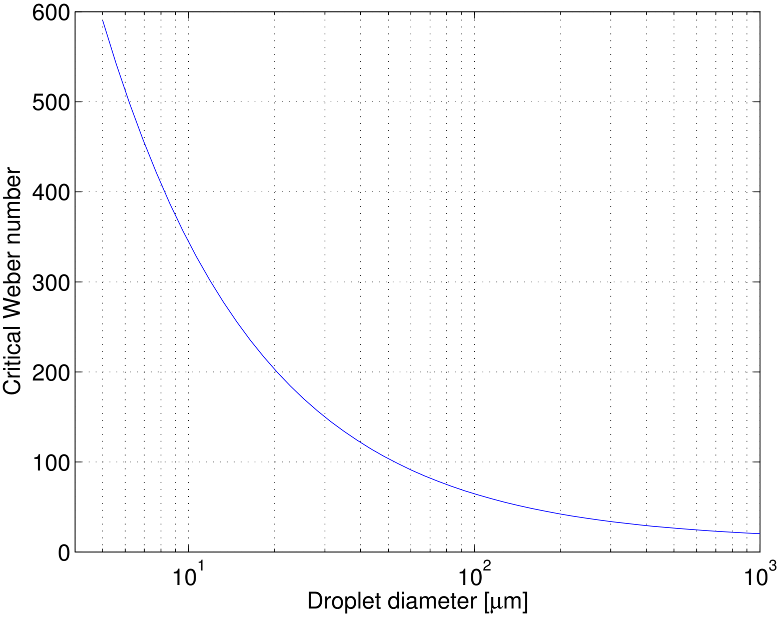

Figure 3.1: *Critical Weber number as a function of droplet diameter. Parameters of the paint from Table 3.1.*

The implication by the large Ohnesorge numbers is that the droplets get successively more difficult to break with the scaling $a^{1.8}$ in the asymptotic limit. More common fluids which are less viscous have only the linear scaling from the Weber number itself.

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[1] Estimated value from Physics Handbook [10, T-1.6] as a measured value is not available.

4 Summary of appended papers

4.1 Paper I — Simulation of Spray Painting in Automotive Industry

The paper describes the software and the numerical methods used to simulate the spray painting of cars. The equations governing the gaseous phase and the Lagrangian particles are shown and their solutions are discussed. Immersed boundary techniques are used to enforce the boundary conditions on the internal interfaces introduces by the spray paint applicator and the target to be painted.

Validations are performed with respect to the number of cells needed to match measured velocity below the applicator to simulated ones. A study of the fraction of particles that need to be simulated is also performed. It is found that good results are obtained by simulating only every 400:th paint particle, a result that can be used to speed up the simulations.

A test case where a flat plate is painted by a single stroke is presented and simulated. Good results are shown for two cases of different process parameters and different paint profiles. A simulation of a car trunk lid is also shown where three paint applicators simultaneously move according to a predefined path to cover the full width of the trunk lid.

4.2 Paper II — Modeling Surface Tension in SPH by Interface Reconstruction using Radial Basis Functions

The paper describes a novel discretization of the surface tension force associated with interfaces between fluids. It is a force that is inversely proportional to the size of the object it is acting on, and at some point it therefore becomes the dominant force, balanced mostly by the pressure gradient. A force of this magnitude is crucial to discretize in an appropriate way as small errors may render the simulation oscillative and unstable.

The contribution describes a way of creating a smooth force field by reconstructing the interface between the fluids in a grid-independent manner. It does so by means of Radial Basis Function [11, 12, 13] with the approximation feature described in [14]. By introducing the η parameter ranging from 0 to 1 the smoothness of the approximation can be tuned to an appropriate level. In the limit of no additional smoothing the approximation turns into an interpolation of the interface that typically varies on the length scale of the computational grid. By adding some smoothing this grid dependence is removed and non-physical locally concave parts of the interface are removed.

The model is validated using two standard test cases for surface tension: The time period of the oscillations of an ellipsis subject to surface tension, and Laplace's law which relates the pressure drop over the interface to the its curvature. Both cases show good results and highlights the discretizations abilities to create stable simulations over long times, without having non-physical disturbances of the velocity field.

4.3 Paper III — Modified TAB Model for Viscous Fluids applied to Breakup in Rotary Bell Spray Painting

The paper describes the application of the Taylor Analogy Breakup (TAB) model [5] to the rotary bell spray painting case. The properties of the paint material differ from what the TAB model has been used for traditionally. In particular, the viscosity of the paint is approximately 100 times that of water. For this reason a correction for large viscosity originally described by Brodkey [9] is applied to the TAB model.

As the application is new to the model its parameters need to be tuned such that the simulated droplet size distributions match measured ones. The global optimization algorithm DIRECT [15] was used to this purpose. One of the five parameters of the model was found to not affect the obtained size distributions and the optimization was reduced to four free variables.

Three different rotation speeds were considered: 30, 40, and 50 thousand revolutions per minute (RPM). Parameters of the original TAB model tuned to the middle case were showed to work reasonably well over the range of rotation speeds, and by optimizing against 30 and 50 thousand RPM simultaneously a better agreement over the full range was obtained. The modified TAB model further increased the accuracy of the model slightly, giving a result were the mode of the distributions was only off by a few micrometers for the 30 and 50 thousand RPM cases.

5 Future work

The third paper describes breakup simulations that are able to capture the overall shape of the size distributions, but the results does not scale entirely correct with the rotation speed of the bell. The tails of the distributions are also not fully captured by the simulation. This needs more work and further validation with different bell cups and process parameters. Ultimately, a model without the need to tune parameters would be preferable.

The surface tension discretization described in the second paper can also be applied to Volume of Fluid simulations with minor modification. By simulating single or pairs of droplets knowledge can be gained about the breakup event. This can later be used to create statistical models taking the micro scale behavior into account.

When an accurate and robust model of the breakup has been implemented it will be included as a module in the software package for simulation of spray painting. By simulating the breakup to obtain droplet size distributions costly and cumbersome measurements can be avoided and the ability to understand and optimize the spray painting process increases.

References

[1] R. Rundqvist, A. Mark, B. Andersson, A. Ålund, F. Edelvik, S. Tafuri, and J. Carlson. "Simulation of Spray Painting in Automotive Industry". *Numerical Mathematics and Advanced Applications 2009*. Ed. by G. Kreiss, P. Lötstedt, A. Målqvist, and M. Neytcheva. Springer Berlin Heidelberg, 2010, pp. 771–779. ISBN: 978-3-642-11795-4. URL: `http://dx.doi.org/10.1007/978-3-642-11795-4_83`.

[2] B. Andersson, S. Jakobsson, A. Mark, F. Edelvik, and L. Davidson. "Modeling Surface Tension in SPH by Interface Reconstruction using Radial Basis Functions". *Proceedings of the* 5^{th} *International SPHERIC Workshop*. Ed. by B.D. Rogers. Manchester (U.K.), June 2010, pp. 7–14.

[3] B. Andersson, S. Jakobsson, A. Mark, F. Edelvik, J. S. Carlson, V. Golovitchev, and L. Davidson. "Modified TAB Model for Viscous Fluids applied to Breakup in Rotary Bell Spray Painting". Report. Dec. 2011.

[4] *IPS Virtual Paint*. `http://www.industrialpathsolutions.com/future-modules/ips-virtual-paint`.

[5] P. O'Rourke and A. Amsden. The TAB method for numerical calculation of spray droplet breakup. *SAE paper 872089* (1987).

[6] M. Pilch and C. Erdman. Use of breakup time data and velocity history data to predict the maximum size of stable fragments for acceleration-induced breakup of a liquid drop. *International Journal of Multiphase Flow* **13**.6 (1987), 741 –757. ISSN: 0301-9322. DOI: `10.1016/0301-9322(87)90063-2`. URL: `http://www.sciencedirect.com/science/article/pii/0301932287900632`.

[7] J. A. Walton. Surface tension and capillary rise. *Physics Education* **7**.8 (1972), 491–498. URL: `http://stacks.iop.org/0031-9120/7/i=8/a=006`.

[8] J. U. Brackbill, D. B. Kothe, and C. Zemach. A continuum method for modeling surface tension. *Journal of Computational Physics* **100**.2 (1992), 335 –354. ISSN: 0021-9991. DOI: `DOI:10.1016/0021-9991(92)90240-Y`.

[9] R. S. Brodkey. *The Phenomena of Fluid Motions*. Addison-Wesley Series in Chemical Engineering. New York, NY, USA: Addison-Wesley Pub. Co., 1967.

[10] C. Nordling and J. Österman. *Physics Handbook*. Sixth edition. Lund, Sweden: Studentlitteratur, 1999.

[11] H. Wendland. *Scattered data approximation*. Vol. 17. Cambridge Monographs on Applied and Computational Mathematics. Cambridge: Cambridge University Press, 2005, pp. x+336. ISBN: 978-0521-84335-5; 0-521-84335-9.

[12] M. D. Buhmann. "Radial basis functions". *Acta numerica, 2000*. Vol. 9. Acta Numer. Cambridge: Cambridge Univ. Press, 2000, pp. 1–38.

[13] M. D. Buhmann. *Radial basis functions: theory and implementations*. Vol. 12. Cambridge Monographs on Applied and Computational Mathematics. Cambridge: Cambridge University Press, 2003, pp. x+259. ISBN: 0-521-63338-9.

[14] S. Jakobsson, M. Patriksson, J. Rudholm, and A. Wojciechowski. A method for simulation based optimization using radial basis functions. *Optimization and Engineering* (2009). DOI: `http://dx.doi.org/10.1007/s11081-009-9087-1`.

[15] D. R. Jones, C. D. Perttunen, and B. E. Stuckman. Lipschitzian optimization without the Lipschitz constant. *J. Optim. Theory Appl.* **79** (1 Oct. 1993), 157–181. ISSN: 0022-3239. DOI: `10.1007/BF00941892`. URL: `http://dl.acm.org/citation.cfm?id=173669.173678`.