

Experimental Study of the parameters affecting the kinetics of coalescence of milk drops

Lara Ventura



UNIVERSITÀ DEGLI STUDI DI SALERNO

Facoltà di Ingegneria
Dipartimento di Ingegneria Industriale
Corso di Laurea in Ingegneria Alimentare

*Experimental Study of the parameters affecting
the kinetics of coalescence of milk drops*

Master's Thesis in Food Engineering

Relatori:

Prof. Ing. Gaetano Lamberti

Prof. Ing. Lilia Ahrnè

Correlatore:

Ing. Loredana Malafronte

Candidato:

Lara Ventura

matricola:0622800149

Anno Accademico 2014/2015



Part of this thesis work has been developed during the Erasmus project at the Chalmers Technical University, in Gothenburg, Sweden.

It has been performed both at the Department of Process and Technology Development of SP The Swedish Institute for Food and Bioscience, under the supervision of Prof. Lilia Arnhè and the PhD candidate Loredana Malafronte, and at Chalmers University under the supervision of Dr. Romain Bordes.



Parte del lavoro di tesi è stato sviluppata nell'ambito del progetto Erasmus presso la Chalmers Technical University, in Gothenburg, Svezia.

In particolare, le attività di ricerca sono state svolte sia presso il Dipartimento di Process and Technology Development del SP The Swedish Institute for Food and Bioscience, sotto la supervisione della Prof.ssa Lilia Arnhè e della dottoranda Loredana Malafronte, sia alla Chalmers sotto la supervisione di Romain Bordes.

Questo testo è stato stampato in proprio, in Times New Roman

La data prevista per la discussione della tesi è il 23/09/2015

Fisciano, 18/09/2015

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Sommario

Lo spray drying, essiccamento per nebulizzazione, è ampiamente utilizzato in diversi settori industriali compreso quello alimentare, farmaceutico e chimico. Si tratta di un processo unitario, in cui si ha la trasformazione di un “liquidfeed” (soluzione, sospensione, emulsione) in un particolato solido secco. Al fine di fare valutazioni sulla dimensione finale della particella prodotta, risulta necessario considerare la natura delle interazioni che si instaurano tra le particelle, queste possono essere suddivise in interazioni: goccia-goccia, goccia-particella e particella-particella.

Soffermandosi sulla prima tipologia e dunque sull’interazione goccia-goccia, incrementando le velocità relative delle due gocce collidenti, è possibile distinguere i seguenti regimi: (i) rimbalzamento, (ii) coalescenza permanente, (iii) separazione e (iv) frantumazione. La nostra attenzione è focalizzata sulla coalescenza permanente, fenomeno fisico che si verifica quando due gocce si uniscono per darne una di entità maggiore.

Dunque al fine di capire la cinetica di coalescenza è analizzato il comportamento di due gocce di latte scremato su una superficie idrofobica, a temperatura ambiente, mediante un tensiometro ottico.

In particolare il lavoro si è concentrato sull’analisi della variazione di tensione superficiale e dell’angolo di contatto dei campioni presi in esame.

Seguendo le linee guida dell’ ADSA, analisi incentrata sul profilo della goccia al fine di trarre informazioni utili quali la tensione superficiale, le immagini delle due gocce sessili registrate tramite il tensiometro ottico sono state analizzate.

Per poter estrarre gli angoli di contatto così come il profilo della goccia, è utilizzato un codice sviluppato in Matlab, in grado di costruire una curva Laplaciana, partendo dalla soluzione di un insieme di equazioni differenziali non lineari, del primo ordine. L'obiettivo è quello di produrre, variando alcuni parametri una curva in grado di dare un "best fitting" del profilo sperimentale della goccia.

Inoltre, è stato analizzato il meccanismo caratterizzante la coalescenza di latte scremato concentrato, tramite freeze-drying, per poter seguire l'evoluzione del processo con il tempo e capire in che modo il contenuto d'acqua influisce sulla cinetica di coalescenza.

.

Abstract

Spray Drying is a widely applied process in several sectors, food, pharmaceutical and chemical industries. It is a one-step processing operation for transforming liquid feeds into dried powders. In order to control powder formation during spray drying, it is important to understand interactions between droplets/particles, such as droplet-droplet, droplet-particle and particle-particle interactions.

These interactions are consequences of droplet/particle collisions and they can lead to several regimes. Based on the level of increasing relative speed during droplet/particle collisions, regimes can be classified as: (i) bouncing, (ii) permanent coalescence, (iii) separation (or grazing) and (iv) shattering.

This work is focused on studying the regime of permanent coalescence of two single droplets. Coalescence is the process by which primary droplets merge to form a second bigger droplet. The aim of this work was to improve understanding of the coalescence-kinetics of two single droplets of skim milk.

Coalescence-kinetics was explored using an optical tensiometer for two droplets of skim milk at room temperature on a hydrophobic surface in terms of changes in surface tension and contact angle. Using the optical tensiometer, contact mechanisms between two sessile droplets were recorded and analyzed following the scheme of ADSA, based on droplet shape analysis. Shapes and contact angles of droplets were extracted by using a code implemented in MATLAB. Sets of first-order, non-linear differential equations were solved to find Laplacian curves, which matches surface profiles of droplets by numerically integrating the Young-Laplace equation, thus providing valuable information of the surface free energy of the system during the coalescence process.

Furthermore, droplets of skim milk with different water contents, obtained by freeze-drying, were used to follow the evolution of coalescence-kinetics as a function of time and water content.

Appendix

A.1 Contact Angle Analyzer

A.1.1 Implementation

1. Start.
 - Turn on the instrument and start program

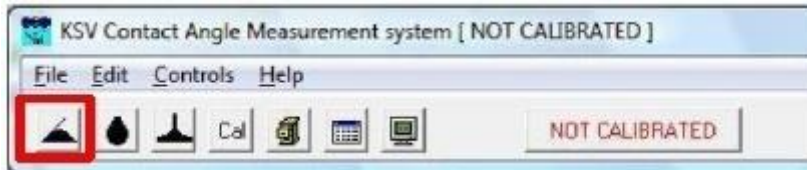


Figure 60: Theta control program

2. Experimental Setup
 - Click the icon inherent to the experiment, in this case: Contact Angle Experiment
 - Select the typology of Solid and Liquid (Heavy Phase)
 - Then, click Start

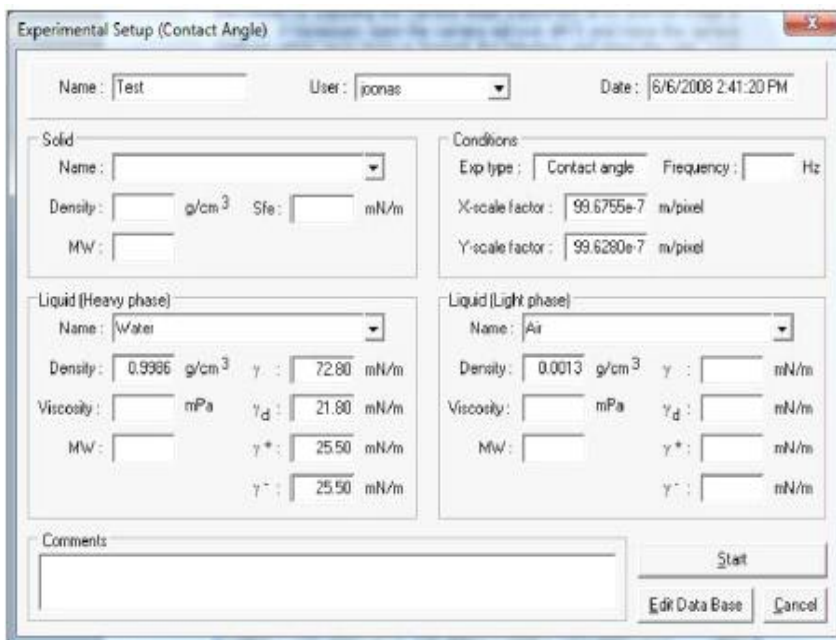


Figure 61: The Experimental Setup Window

3. Image Recording

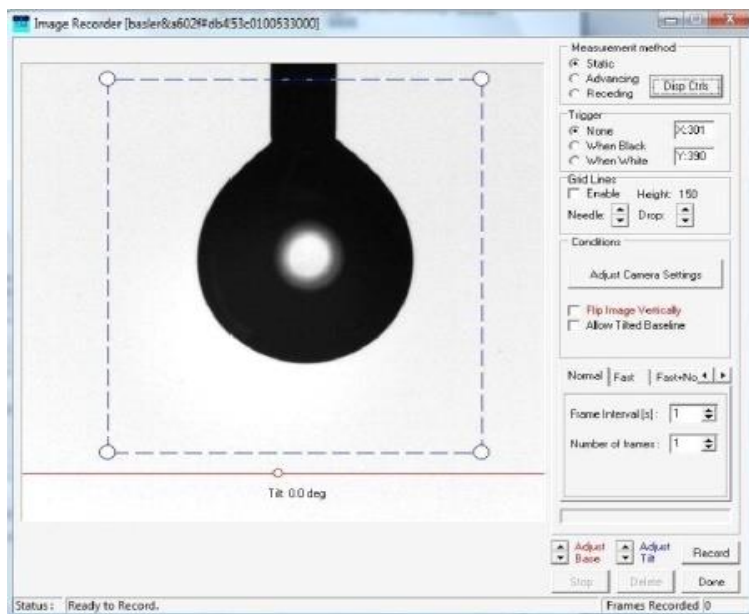


Figure 62: The Image Recorder captures the measurement data

- Lift or lower the sample stage until the solid is visible on the bottom part of the screen.
- Locate the needle on the center and at the top of the screen
- Select a Record Mode, Normal/Fast/ Fast + Normal
- To adjust the focus of the image turn the camera lens focus adjustment until the image is focused.
- Click Adjust Camera Setting to get appropriate intensity (green on Focusing window)
- Approach the needle to the sample stage to create the drop
- Click Record and wait for the images to be recorded and press Done



Figure 63: Adjust Camera Settings

4. Curve fitting

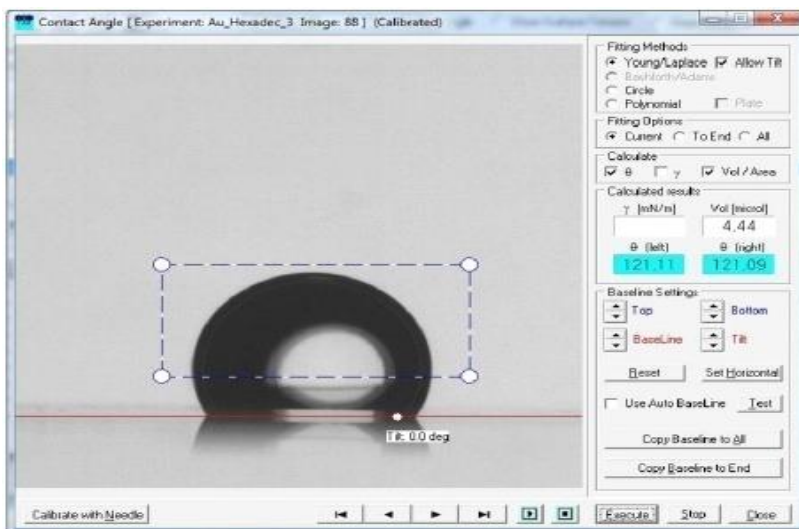


Figure 64 : The Curve fitting window

- Click Calibrate with the Needle, since the diameter of needle 0.71 mm is known
 - Check visually the position of the BaseLine and set it manually by clicking and dragging on the white circle. Place the blue box around the entire drop profile and press Execute.
5. Data Analysis

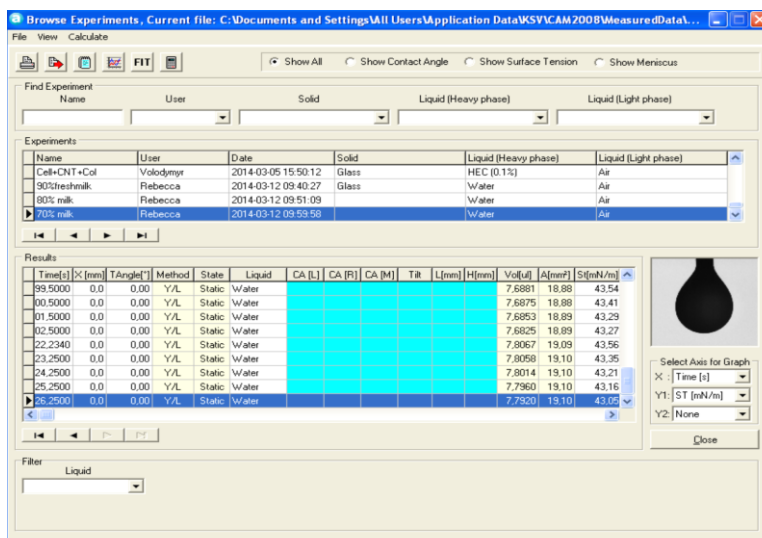


Figure 65: Conducted Measurements are analyzed in the Browse Exps.

B.1 Program Code

%B.1.1 Extraction of frames

%Referencing to Matlab file “extractionframes.m”.

1. *%This function is used in order to extract the frame from the movie of coalescence.*
 2. *% Clear and close all opened materials*
 3. **close all**
 4. **clear all**
 5. *% selection of the frames to analyze*
 6. **for** k=1:1029
 7. *% reading of the movie and storing the frame in a new variable*
 8. **obj1=mmreader('14movie.avi');**
 9. **fig=read(obj1,k);**
 10. *% show the frame*
 11. **I=imshow(fig);**
 12. *% save the extracted frame specifying the name and the format of the new image*
 13. **saveas(I,sprintf('coalescence14.%d.jpg',k));**
 14. **end**
-

%B.1.2 Movie analysis

```

1.  %The function used to analyze the movie is movieanalysis.m, in
    detail to the milk at 95% of water content.
2.  close all
3.  clear all
4.  measuringangle=input('typology of angle:1-right,2-left:');%
    Choose the typology of angle
5.  for r=272:1029 %number of frames
6.  [valueapex,height,angle,angle1,angle2]=evaluation(r,measuringa
    ngle)% recall the function evaluation.m
7.  end
8.  %export data from txt to excel
9.  load('ellipse.txt')%ellipse data
10. if measuringangle==1
11. load('dataright.txt'); % load the data concerning the right angle
    inMatlab
12. Headers={'rangle','dropheight','apexvalue'};% vector containing
    a text string
13. % Import the results in excel
14. xlswrite('95%milkrigh',Headers,1,'A1');
15. xlswrite('95%milkrigh',dataright(:,1),1,'A3');
16. xlswrite('95%milkrigh',dataright(:,2),1,'B3');
17. xlswrite('95%milkrigh',dataright(:,3),1,'C3');
18. winopen('95%milkrigh.xls')% open the excel window to the
    user
19. xlswrite('95%milkeellipse',ellipse(:,1),1,'A3');
20. xlswrite('95%milkeellipse',ellipse(:,2),1,'B3');
21. elseif measuringangle==2% other condition true for left angle
22. load('dataleft.txt');
23. Headers={'langle','dropheight','apexvalue'};
24. xlswrite('95%milklef',Headers,1,'A1');
25. xlswrite('95%milklef',dataleft(:,1),1,'A3');
26. xlswrite('95%milklef',dataleft(:,2),1,'B3');
27. xlswrite('95%milklef',dataleft(:,3),1,'C3');
28. winopen('95%milklef.xls')
29. xlswrite('95%milkeellipse',ellipse(:,1),1,'C3');
30. xlswrite('95%milkeellipse',ellipse(:,2),1,'D3');
31. end

```

%B.1.3 Determining the contact Angle on a Substrate

1. *% The function evaluation.m is used in order to measure the contact angle so as the height and the radius at the apex, of the droplet.*
 2. *% the input are r, the number of the frame analyzed and measuring angle, a variable that defines the type of angle analyzed, as output the measurement of angle and all the elements needed to define the drop shape.*
 3. *function[valueapex,height,angle,angle1,angle2]=evaluation(r,measuringangle)*
 4. *%selection of the image stored in a new file named droplet*
 5. *droplet=strcat('coalescence14.',num2str(r),'.jpg')*
 6. *I=imread(droplet);% importation of the image of the droplet*
 7. *I2=im2bw(I,0.5);% make black and white image*
 8. *% Crop an area for the droplet*
 9. *% is an automatic selection of the object of interest [x, y,w,h]*
 10. *% define a rectangular area*
 11. *rect=[200 300 600 200];*
 12. *I2=imcrop(I2,rect);*
 13. *% edge detection*
 14. *BW1 = edge(I2,'sobel');*
 15. *% identification of the droplet from the background*
 16. *Acrop=BW1;*
 17. *[m,n]=size(Acrop);*
 18. *k=1;% initiaziling the variable k*
 19. **for** *i=1:n*
 20. **for** *j=1:m*
 21. **if** *Acrop(j,i)==1*
 22. *y(k)=j;*
 23. *x(k)=i;*
 24. *k=k+1;*
 25. **end**
 26. **end**
 27. **end**
 28. *% Recall the experimental data using new variables*
 29. *a=size(y);% length of the vector y*
 30. *b=a((2));*
 31. *y_=y;*
 32. *x_=x;*
 33. *% Approximation of the droplet trough an ellipse*
-

```
34. % construction of a vector of ten points starting from the left
    boundary
35. w=1;% initializing variable used as index for the vector x_l
36. s=10;
37. for N=1:s
38. x_l(w)=x(N);% define as column vector x_l containing x
    coordinates
39. y_l(w)=y(N);
40. w=w+1;
41. end
42. % construction of a vector of ten points starting from the right
    boundary
43. e=size(x);
44. e=e(2);
45. f=(e-9);
46. q=1; % initializing of the variable used as index for the vector x_r
47. for N=f:e
48. x_r(q)=x(N);
49. y_r(q)=y(N);
50. q=q+1;
51. end
52. % a vector containing the twenty points is generated
53. t=size(x_r);
54. t=t(2);
55. x_st=zeros(1,s+t); %x_st vector containing the x coordinates for
    the generation of the straightline
56. y_st=zeros(1,s+t);
57. m=1;
58. for i=1:s
59. x_st(m)=x_l(i);
60. y_st(m)=y_l(i);
61. m=m+1;
62. end
63. n=1;
64. for i=(s+1):(s+t)
65. x_st(i)=x_r(n);
66. y_st(i)=y_r(n);
67. end
68. % Fitting of the points trough a linear function, in order to find
    the slope and the intercept
```

```
69. p=polyfit(x_st,y_st,1);
70. m=p(1);
71. q=p(2);
72. for i=1:b
73. y_st_1(i)=m.*x_(i)+q;
74. end
75. % Difference between the two functions, the straightline and the
    experimental profile obtained from edge detection, in order to
    clean the imperfections given from the detection.
76. for i=1:b
77. dati_y(i)=y_st_1(i)-y_(i);% difference between the y data
78. if dati_y(i)>0% if the difference is greater than zero, the y
    coordinate is equal to it
79. dati_ord(i)=dati_y(i);
80. else
81. dati_ord(i)=0;
82. end
83. end
84. % Store the new data, in order to obtain the correct drop profile
85. for i=1:b
86. y_(i)=dati_ord(i);
87. end
88. %Fitting of the experimental data with an ellipse
89. % choice of random parameters
90. alfa=120;
91. beta=100 ;
92. gamma=50 ;
93. psi=0 ;% eccentricity
94. clear parameters
95. clear err
96. % define the parameters to optimize the function
97. parameters=[alfa,beta,gamma,psi];
98. %Optimization
99. % multidimensional unconstrained non linear minimization, to
    find the combination of parameters for which the function has a
    minimum
100. [parameters,fval,exitflag,output]=fminsearch(@(parameters)
    errorellipse(parameters,x_,y_),parameters);
101. [err]=errorellipse(parameters,x_,y_);% recall the function
    errorellipse
```

```
102. ex(r)=exitflag; %to verify the iteration
103. output;
104. % The values of the parameters are replaced in the function
    ellipseoptimal.m, in order to construct the ellipse, that gives a
    best fitting of the experimental droplet
105. [yellipse,xellipse]=optimalellipse(parameters,x_,y_);
106. % intersection with axes
107. optparameters=parameters;
108. alfa=optparameters(1);% extraction of each parameter
109. beta=optparameters(2);
110. gamma=optparameters(3);
111. psi=optparameters(4);
112. x0=gamma-alfa*sqrt(1-(psi/beta)^2); % the intersection with
    axis at the left of the droplet center
113. x1=gamma+alfa*sqrt(1-(psi/beta)^2); % intersection with axis
    at the right of the center
114. % first estimate of the angles,evaluating those given from the
    ellipse fitting
115. angle=acos((x0-gamma)/(alfa));
116. angle1=90-(angle*180)/(pi); % conversion in radians
117. clear angle
118. angle2=acos((x1-gamma)/(alfa));
119. angle2=90-(angle2*180)/(pi);
120. h=(psi+beta); %height of the droplet
121. fid=fopen('ellipse.txt','a'); %open the data file
122. fprintf(fid,' %6.2f %6.2f\n',angle1,angle2); %write the values
    into the file
123. fclose(fid);
124. % Store the experimental data in other variables not to generate
    confusion in Matlab
125. x_n=x;
126. y_n=y;
127. % Definition of the apex, starting from ellipse
128. apex_x=gamma;
129. apex_z=beta;
130. % Introduction to the core of the code, definition of all
    parameters and steps needed to solve Laplace-Young equation
131. % Fluid properties
132. wc=0.95;%water content in this case
133. u=(wc/ (1-wc));
```

```

134. ds=1470;% kg/m^3;% solid density
135. dw=1000;%kg/m^3%water density
136. rho_m=((u+1)/(u/dw+1/ds))/10^3; %density of fluid, [g/cm^3]
137. rho_a=0.0012;%density of surround fluid,typically air
138. g=981.7;% gravity acceleration [cm/s^2]
139. sig=49.913222;% surface tension [dyne/cm] for milk at 95% of
    wc
140. %Definition of c, capillarity constant in unit of 1/cm^2
141. c=((rho_m-rho_a)*g)/sig;
142. %Conversion
143. %through ImageJ
144. %0.71mm(calibration for the needle of the tensiometer)=102.82
    pixels
145. %change the coordinate in X and Z
146. %conversion to cm and replacement of x with X and of y with Z
147. Xi=x_n(:)*0.00069;
148. Zi=y_n(:)*0.00069;
149. % conversion for the apex
150. apex_x=apex_x*0.00069;
151. apex_z=apex_z*0.00069;
152. % Collocation of the origin in the apex origin
153. Xi_new=(-Xi+apex_x)*c^0.5;
154. Zi_new=(-Zi+apex_z)*c^0.5;
155. %conversion for x0 e x1
156. x0=x0*0.00069;
157. x1=x1*0.00069;
158. x0=(-x0+apex_x)*c^0.5;
159. x1=(-x1+apex_x)*c^0.5;
160. % Selection of the positive data, for right angle
161. k=1;
162. a=size(Xi_new);
163. if measuringangle==1
164. for i=1:a
165. if Xi_new(i)>=0 &Xi_new(i)<= x0% the data must be positive
        and lower than x0, the intersection point
166. Xi_new_pos_1(k)=Xi_new(i);
167. Zi_new_pos_1(k)=Zi_new(i);
168. k=k+1;
169. end
170. end

```

```

171. elseif measuringangle==2% selection of data needed to define
    the left angle
172. for i=1:a
173. if Xi_new(i)<=0 &Xi_new(i)>= x1
174. Xi_new_pos_3(k)=-Xi_new(i);
175. Zi_new_pos_3(k)=Zi_new(i);
176. k=k+1;
177. end
178. end
179. end
180. %condition true only for left angle
181. If measuringangle==2
182. lungh=length(Zi_new_pos_3);
183. k=lungh;
184. fori =1:lungh
185. Xi_new_pos_1(k)=Xi_new_pos_3(i);% store the coordinate, in
    order not to introduce other variables for the following
    functions
186. Zi_new_pos_1(k)=Zi_new_pos_3(i);
187. k=k-1;
188. end
189. end
190. % Defined the experimental points,b and c is possible to solve
    the set of ordinary differential equation
191. clear err
192. b=0.1292*2; % apex of curvature of first tentative
193. [err]=errorlaplace(b,c,Zi_new_pos_1,Xi_new_pos_1);% err is
    the output of the newfunctionerrorlaplace.m
194. %Optimization for Laplace
195. clear xopt
196. [xopt]=fminsearch(@errorrlaplace,b,[],c,Zi_new_pos_1,Xi_new
    _pos_1); % search the b value that gives the minimum of the
    error function
197. %optimal value of b now bb,solve Laplace
198. bb=xopt;
199. [ x_ly_1,z_ly_1,Phi_ly_1]
    =optimalaplace(bb,c,Xi_new_pos_1;Zi_new_pos_1);
200. % evaluation again of the coordinates needed to construct the
    theoretical profile, with the value of optimal b
201. % Plot the experimental profile and the theoretical one

```

```

202. linesize=3;
203. textsize=15;
204. plot(Xi_pos,Zi_pos,'b','LineWidth',linesize)%experimental data
205. hold on
206. plot(x_ly_1,z_ly_1,'g')%Laplace's data
207. set(gca,'YDir','reverse');% rotation of the graph
208. xlabel('value of x')
209. ylabel('value of z')
210. title('Fitting Drop')
211. hold off
212. % Output variables
213. rightangle=max(Phi_ly_1);% right angle[degrees]
214. height=max(z_ly_1);%height of the droplet [cm]
215. error=err;
216. valueapex=xopt;
217. %Import results into a txt.file
218. if measuringangle==1
219. fid=fopen('dataright.txt','a'); %open the data file
220. fprintf(fid,' %6.4f %6.4f %6.4f\n',angle,height,valueapex);
    %write the results into the file
221. fclose(fid); %close the file
222. elseif measuringangle==2
223. fid=fopen('dataleft.txt','a'); %open the data file
224. fprintf(fid,' %6.4f %6.4f %6.4f\n',angle,height,valueapex);
    %write the values into the file
225. fclose(fid);
226. end
227. end

```

%B.1.3.1 Fitting trough an ellipse

1. %The function considered is errorellipse.m
 2. **function**[err]=errorellipse(parameters,x_,y_)
 3. alfa=parameters(1);%parameters characterizing the ellipse, defined in input
 4. beta=parameters(2);
 5. gamma=parameters(3);
 6. psi=parameters(4);
 7. %Knowing the parameters is possible to construct the ellipse starting from experimental data
 8. s=size(x_);
-

```

9. s=s(2);
10. for i =1:s
11. if (psi/beta)>1% to select only positive roots
12. y_ellipse(i)=0;
13. elseif (x_(i)>=(gamma-alfa*(sqrt(1-(psi/beta).^2)))
    &&x_(i)<=(gamma+alfa*(sqrt(1-(psi/beta).^2))))
14. y_ellipse(i)=(beta*(sqrt(1-((x_(i)-gamma)/alfa).^2))+psi);%
    definition of the ordinata for ellipse
15. else
16. y_ellipse(i)=0;
17. end
18. end
19. %Evaluation of the error,as the difference between the ordinata
    of the two functions, the drop profile and ellipse
20. for i=1:s
21. res(i)=(y_(i)-y_ellipse(i)).^2;
22. end
23. %sum the errors
24. err=sum(res);
25. end

```

%B.1.3.2 Optimization ellipse

```

1. % Reference to the function optimalellipse.m, has been
    constructed the ellipse with the optimal combination of
    parameters
2. function[yellipse,xellipse]=optimalellipse(parameters,x_,y_)
3. alfa=parameters(1);
4. beta=parameters(2);
5. gamma=parameters(3);
6. psi=parameters(4);
7. s=size(x_);
8. s=s(2);
9. for i =1:s
10. if (psi/beta)>1
11. yellipse(i)=0;
12. elseif (x_(i)>= (gamma-alfa*(sqrt(1-(psi/beta).^2))) &&
    x_(i)<=(gamma+alfa*(sqrt(1-(psi/beta).^2))))
13. yellipse(i)=(beta*(sqrt(1-((x_(i)-gamma)/alfa).^2))+psi);
14. else
15. yellipse(i)=0;

```

16. **end**

17. **xellipse(i)=x_(i);end**

%B.1.3.3 Laplace equation

1. *% LAPLACE defines the ordinary differential equations to be solved.*
2. *% z=drop height*
3. *% x=distance from axis to drop interface*
4. *% phi=contact angle*
5. *% 1/b=radius of curvature at apex*
6. *% s=arc length*
7. *% NON-DIMENSIONALIZE Z,X,S,B USING $C^{(1/2)}$*
8. *% $B=b*c^{(1/2)}$*
9. *% $X=x*c^{(1/2)}$*
10. *% $Z=z*c^{(1/2)}$*
11. *% $S=s*c^{(1/2)}$*
12. *% No need to define X,Z,S for equations*
13. *% $Z=y(1)$; $Z'=dy(1)$; Z' is with respect to S*
14. *% $X=y(2)$; $X'=dy(2)$; X' is with respect to S*
15. *% $\phi=y(3)$; $\phi'=dy(3)$; ϕ' is with respect to S*
16. *% $Z'=\sin(\phi)$*
17. *% $X'=\cos(\phi)$*
18. *% $\phi'=2/B+Z-(\sin(\phi)/X)$*
19. *function [dy]=laplace(s,y,b,c)*
20. *dy = zeros(3,1); % a column vector*
21. *B=b*c^{.5}; % non-dimensionalized curvature at apex*
22. *dy(1)=sin(y(3));*
23. *dy(2)=cos(y(3));*
24. *dy(3)=(2/B)+y(1)-(sin(y(3))/y(2));*
25. **end**

%B.1.3.4 Error function for b

1. *function[err]=errorlaplace(b,c,Zi_new_pos_1,Xi_new_pos_1)*
2. *S_span=(0:.001:1);%S_span is the step variable for ode45 solver*
3. *[S,Y]=ode45(@laplace,S_span,[0 1e-100 0],[],b,c);*
4. *x_ly(:,1)=Y(:,2);*
5. *z_ly(:,1)=Y(:,1);*
6. *S_ly(:,1)=S(:,1);*
7. *Phi_ly(:,1)=Y(:,3)*(180/pi);*
8. *k=1;*

```
9. b=max(Zi_new_pos_1);
10. a=size(z_ly);
11. fori=1:a
12.   if z_ly(i)<b% selection of the points considering the maximum
      of the experimental data
13.     z_ly_1(k)=z_ly(i);
14.     x_ly_1(k)=x_ly(i);
15.     k=k+1;
16.   end
17. end
18. f=size(x_ly_1);
19. f=f(2);
20. %Comparison between only selected points
21. primox=x_ly(1);
22. primoz=z_ly(1);
23. mediox=x_ly(round(f/2));
24. medioz=z_ly(round(f/2));
25. finalex=x_ly(f);
26. finalez=z_ly(f);
27. s=round(f/2);
28. secondox=x_ly(round(f-s/2));%from the basis to the middle
      point
29. secondoz=z_ly(round(f-s/2));
30. %fifth point
31. quintox=x_ly(round(s/2));
32. quintoz=z_ly(round(s/2));
33. %sixth point
34. met=round(s/2);
35. sestox=x_ly(round(f-s/2));
36. sestoz=z_ly(round(f-s/2));
37. %seventh point
38. sett=round(met/2);
39. settimox=x_ly(round(f-sett/2));
40. settimoz=z_ly(round(f-sett/2));
41. %eight (chosen this value because is to close to the point of
      interest)
42. ottavox=x_ly(f-22);
43. ottavoz=z_ly(f-22);
44. %selection the same points but using experimental data
45. d=size(Xi_new_pos_1);
```

```

46. d=d(2);
47. primox1=Xi_new_pos_1(d);
48. primoz1=Zi_new_pos_1(d);
49. mediox1=Xi_new_pos_1(round(d/2));
50. medioz1=Zi_new_pos_1(round(d/2));
51. finalex1=Xi_new_pos_1(1);
52. finalez1=Zi_new_pos_1(1);
53. e=round(d/2);
54. secondox1=Xi_new_pos_1(round(e/2));
55. secondoz1=Zi_new_pos_1(round(e/2));
56. %fifth point
57. quintox1=Xi_new_pos_1(round(d-e/2));
58. quintoz1=Zi_new_pos_1(round(d-e/2));
59. %sixth point
60. mes=round(e/2);
61. sestox1=Xi_new_pos_1(round(mes/2));
62. sestoz1=Zi_new_pos_1(round(mes/2));
63. setts=(mes/2);
64. settimox1=Xi_new_pos_1(round(setts/2));
65. settimoz1=Zi_new_pos_1(round(setts/2));
66. ottavox1=Xi_new_pos_1(22);
67. ottavoz1=Zi_new_pos_1(22);
68. %evaluation of error
69. xmax=Xi_new_pos_1(1);%define the maximum of data
70. %parameters that are important to define the error
71. eps=10^(-3);
72. a=1;
73. %error calculated as the distance between the experimental
    point and the one obtained from Laplace,the error is weighted
74. res1=(0.5)*(1/((abs(primox1-xmax))^a+eps))*((primox-
    primox1)^2+(primoz-primoz1)^2);
75. res2=(0.5)*(1/((abs(mediox1-xmax))^a+eps))*((mediox-
    mediox1)^2+(medioz-medioz1)^2);
76. res3=(0.5)*(1/((abs(finalex1-xmax))^a+eps))*((finalex-
    finalex1)^2+(finalez-finalez1)^2);
77. res4=(0.5)*(1/((abs(secondox1-xmax))^a+eps))*((secondox-
    secondox1)^2+(secondoz-secondoz1)^2);
78. res5=(0.5)*(1/((abs(quintox1-xmax))^a+eps))*((quintox-
    quintox1)^2+(quintoz-quintoz1)^2);

```

```

79. res6=(0.5)*(1/((abs(sestox1-xmax))^a+eps))*((sestox-
sestox1)^2+(sestoz-sestoz1)^2);
80. res7=(0.5)*(1/((abs(settimox1-xmax))^a+eps))*((settimox-
settimox1)^2+(settimoz-settimoz1)^2);
81. res8=(0.5)*(1/((abs(ottavox1-xmax))^a+eps))*((ottavox-
ottavox1)^2+(ottavoz-ottavoz1)^2);
82. err=(res1+res2+res3+res4+res5+res6+res7+res8)*1000;
83. end

```

%B.1.3.5 Optimization Laplace

1. *%The function optimalaplace.m is used in order to construct the theoretical profile starting with the optimal value of b*

```

2. S_span=(0:.001:1);
3. [S,Y]=ode45(@laplace,S_span,[0 1e-100 0],[[],bb,c);
4. x_ly(:,1)=Y(:,2);
5. z_ly(:,1)=Y(:,1);
6. S_ly(:,1)=S(:,1);
7. Phi_ly(:,1)=Y(:,3)*(180/pi);
8. k=1;
9. b=max(Zi_new_pos_1);
10. a=size(z_ly);
11. for i=1:a
12. if z_ly(i)<b
13. Phi_ly_1(k)=Phi_ly(i);
14. z_ly_1(k)=z_ly(i);
15. x_ly_1(k)=x_ly(i);
16. k=k+1;
17. end
18. end
19. end

```

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Acknowledgements

I am grateful to Prof. Gaetano Lamberti, for his big patience and support, he has been a lighthouse for me during this thesis work.

I am deeply grateful to Prof. Lilia Ahrnè, for giving me the possibility to make a new experience and to work with her research group.

I would like to express my gratitude to my co-supervisor during the project, Dr. Loredana Malafronte, for her help, suggestions and all the encouragements, she has been a friendly co-supervisor.

My sincere thanks go to all the people of the Department of Process and Technology Development of SP and to the entire group of Transport Phenomena & Processes at University of Salerno, in particular to Diego Caccavo, for the daily little helps.

I want to thank my family for believing in me, a particular thanks goes to my uncle: I always feel his presence in the daily little good things that happen to me.

I wish to express my gratitude to my fellow students at UNISA, for their big support.

Special thanks also to my Erasmus friends, we have spent unforgettable moments together.

Salerno 18/09/2015

Lara Ventura

