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

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

Master's Thesis in Food Engineering

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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 LoredanaMalafronte, and at Chalmers University under the supervision of Dr. RomainBordes.

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

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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.

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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 hydropobic 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

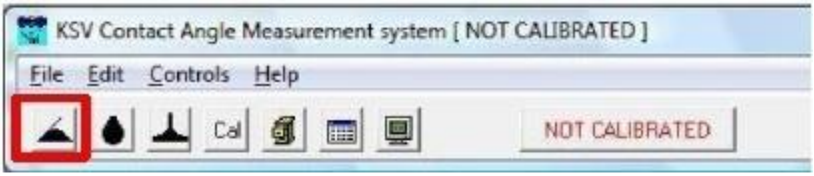

Figure 60: Theta control program

2. Experimental Setup

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

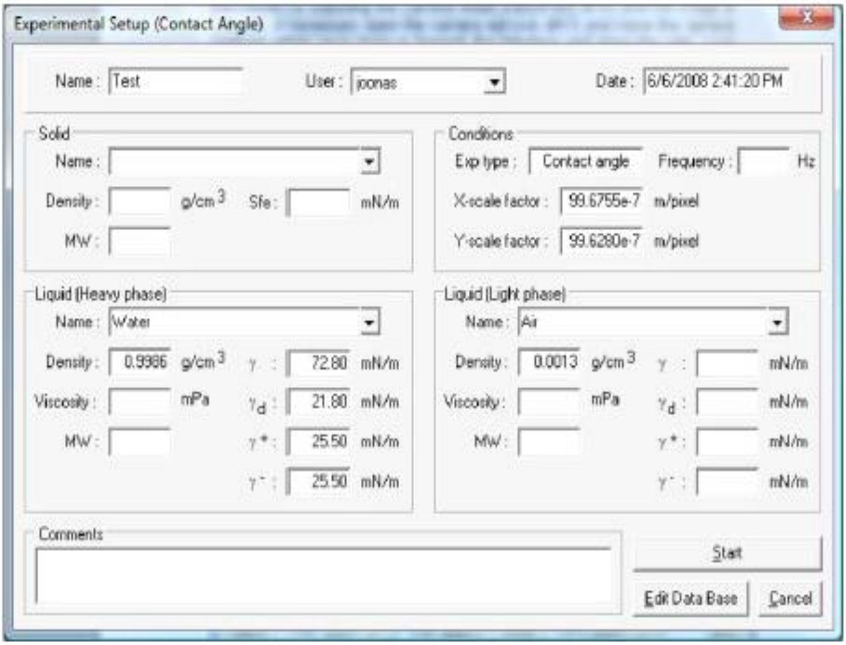

Figure 61: The Experimental Setup Window

3. Image Recording

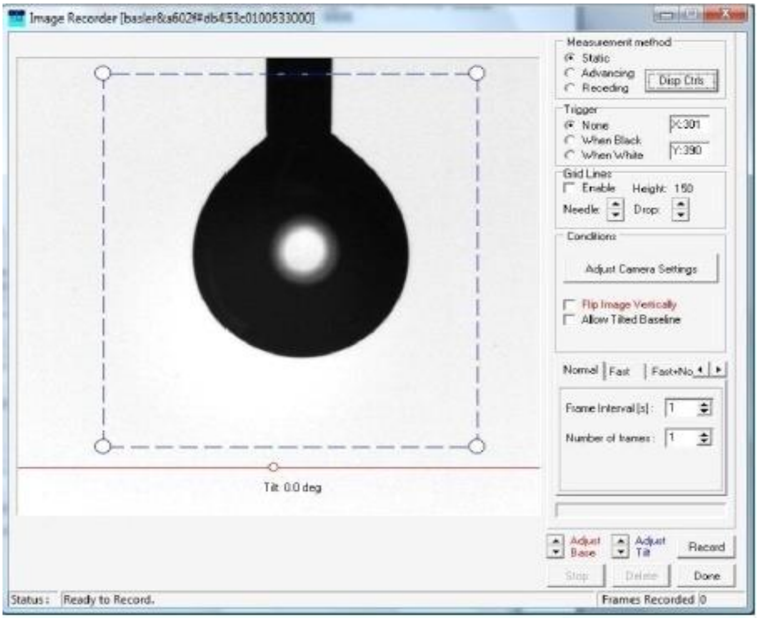

Figure 62: The Image Recorder captures the measurement data

- 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

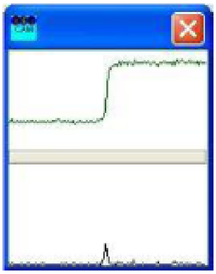

Figure 63: Adjust Camera Settings

4. Curve fitting

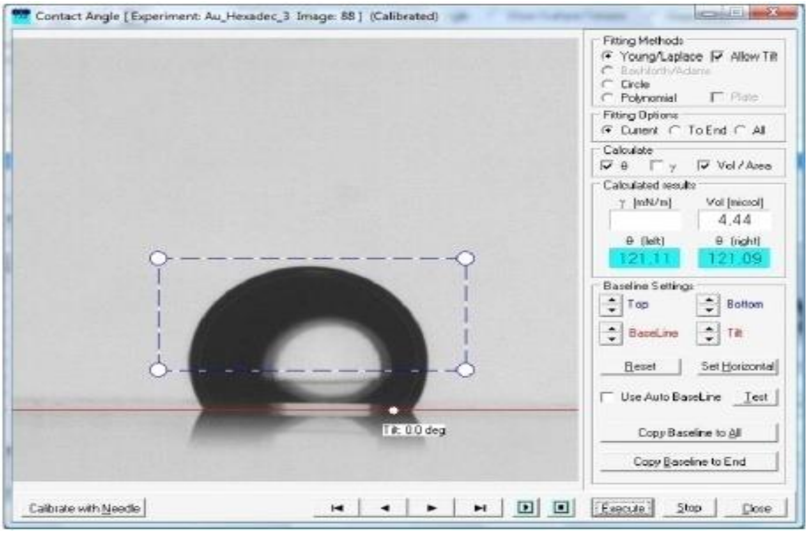

Figure 64 : The Curve fitting window

- 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

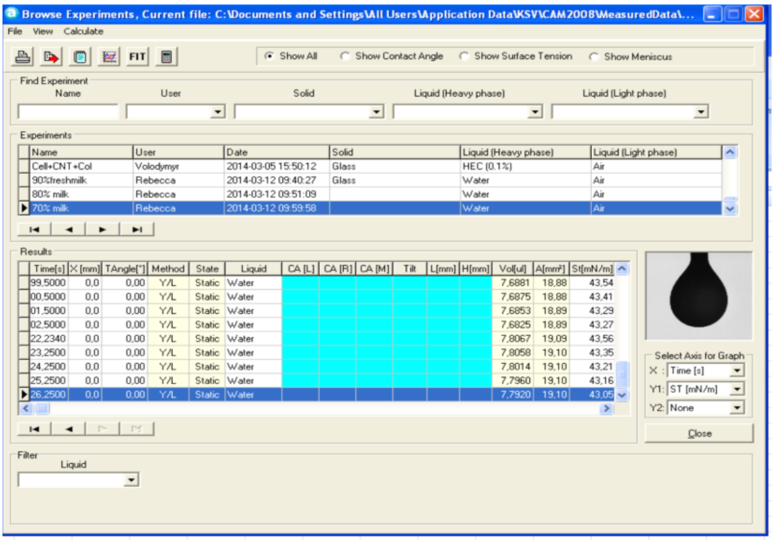

Figure 65: Conducted Measurements are analyzed in the Browse Exps.

B.1 Program Code

%B.1.1 Extraction of frames

%Referencing to Matlab file “extractionframes.m”.

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

%B.1.2 Movie analysis

```
%The function used to analyze the movie is movieanalysis.m, in detail to the milk at 95% of water content.
close all
clear all
measuringangle=input('typology of angle:1-right,2-left:');% Choose the typology of angle
for r=272:1029 %number of frames
[valueapex,height,angle,angle1,angle2]=evaluation(r,measuringangle)% recall the function evaluation.m
end
%export data from txt to excel
load('ellipse.txt')%ellipse data
if measuringangle==1
load('dataright.txt'); % load the data concerning the right angle inMatlab
Headers={'rangle','dropheight','apexvalue'};% vector containing a text string
% Import the results in excel
xlswrite('95%milkright',Headers,1,'A1');
xlswrite('95%milkright',dataright(:,1),1,'A3');
xlswrite('95%milkright',dataright(:,2),1,'B3');
xlswrite('95%milkright',dataright(:,3),1,'C3');
winopen('95%milkright.xls')% open the excel window to the user
xlswrite('95%milkellipse',ellipse(:,1),1,'A3');
xlswrite('95%milkellipse',ellipse(:,2),1,'B3');
elseif measuringangle==2% other condition true for left angle
load('dataleft.txt');
Headers={'langle','dropheight','apexvalue'};
xlswrite('95%milkleft',Headers,1,'A1');
xlswrite('95%milkleft',dataleft(:,1),1,'A3');
xlswrite('95%milkleft',dataleft(:,2),1,'B3');
xlswrite('95%milkleft',dataleft(:,3),1,'C3');
winopen('95%milkleft.xls')
xlswrite('95%milkellipse',ellipse(:,1),1,'C3');
xlswrite('95%milkellipse',ellipse(:,2),1,'D3');
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,heigth,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*

```
% construction of a vector of ten points starting from the left boundary
w=1;% initializing variable used as index for the vector x_l
s=10;
for N =1:s
x_l(w)=x(N);% define as column vector x_l containing x coordinates
y_l(w)=y(N);
w=w+1;
end
% construction of a vector of ten points starting from the right boundary
e=size(x);
e=e(2);
f=(e-9);
q=1; % initializing of the variable used as index for the vector x_r
for N=f:e
x_r(q)=x(N);
y_r(q)=y(N);
q=q+1;
end
% a vector containing the twenty points is generated
t=size(x_r);
t=t(2);
x_st=zeros(1,s+t); %x_st vector containing the x coordinates for the generation of the straightline
y_st=zeros(1,s+t);
m=1;
for i=1:s
x_st(m)=x_l(i);
y_st(m)=y_l(i);
m=m+1;
end
n=1;
for i=(s+1):(s+t)
x_st(i)=x_r(n);
y_st(i)=y_r(n);
end
% Fitting of the points trough a linear function, in order to find the slope and the intercept
```

```
p=polyfit(x_st,y_st,1);
m=p(1);
q=p(2);
for i=1:b
y_st_1(i)=m.*x_(i)+q;
end
% 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.
fori=1:b
dati_y(i)=y_st_1(i)-y_(i);% difference between the y data
ifdati_y(i)>0% if the difference is greater than zero, the y coordinate is equal to it
dati_ord(i)=dati_y(i);
else
dati_ord(i)=0;
end
end
% Store the new data, in order to obtain the correct drop profile
for i=1:b
y_(i)=dati_ord(i);
end
%Fitting of the experimental data with an ellipse
% choice of random parameters
alfa=120;
beta=100 ;
gamma=50 ;
psi=0 ;% eccentricity
clear parameters
clear err
% define the parameters to optimize the function
parameters=[alfa,beta,gamma,psi];
%Optimization
% multidimensional unconstrained non linear minimization, to find the combination of parameters for which the function has a minimum
[parameters,fval,exitflag,output]=fminsearch(@(parameters) errorellipse(parameters,x_,y_),parameters);
[err]=errorellipse(parameters,x_,y_);% recall the function errorellipse
```

```
ex(r)=exitflag; %to verify the iteration
output;
% 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
[yellipse,xellipse]=optimalellipse(parameters,x_,y_);
% intersection with axes
optparameters=parameters;
alfa=optparameters(1);% extraction of each parameter
beta=optparameters(2);
gamma=optparameters(3);
psi=optparameters(4);
x0=gamma-alfa*sqrt(1-(psi/beta)^2); % the intersection with axis at the left of the droplet center
x1=gamma+alfa*sqrt(1-(psi/beta)^2); % intersection with axis at the right of the center
% first estimate of the angles,evaluating those given from the ellipse fitting
angle=acos((x0-gamma)/(alfa));
angle1=90-(angle*180)/(pi); % conversion in radians
clear angle
angle2=acos((x1-gamma)/(alfa));
angle2=90-(angle2*180)/(pi);
h=(psi+beta); %height of the droplet
fid=fopen('ellisse.txt','a'); %open the data file
fprintf(fid,' %6.2f %6.2f\n',angle1,angle2); %write the values into the file
fclose(fid);
% Store the experimental data in other variables not to generate confusion in Matlab
x_n=x;
y_n=y:
% Definition of the apex, starting from ellipse
apex_x=gamma;
apex_z=beta;
% Introduction to the core of the code, definition of all parameters and steps needed to solve Laplace-Young equation
% Fluid properties
wc=0.95;%water content in this case
u=(wc/ (1-wc));
```

```
ds=1470;% kg/m^3;% solid density
dw=1000; %kg/m^3%water density
rho_m=((u+1)/(u/dw+1/ds))/10^3; %density of fluid, [g/cm^3]
rho_a=0.0012;%density of surround fluid,typically air
g=981.7;% gravity acceleration [cm/s^2]
sig=49.913222;% surface tension [dyne/cm] for milk at 95% of wc
%Definition of c, capillarity constant in unit of 1/cm^2
c=((rho_m-rho_a)*g)/sig;
%Conversion
%through ImageJ
%0.71mm(calibration for the needle of the tensiometer)=102.82 pixels
%change the coordinate in X and Z
%conversion to cm and replacement of x with X and of y with Z
Xi=x_n(:)*0.00069;
Zi=y_n(:)*0.00069;
% conversion for the apex
apex_x=apex_x*0.00069;
apex_z=apex_z*0.00069;
% Collocation of the origin in the apex origin
Xi_new=(-Xi+apex_x)*c^0.5;
Zi_new=(-Zi+apex_z)*c^0.5;
%conversion for x0 e x1
x0=x0*0.00069;
x1=x1*0.00069;
x0=(-x0+apex_x)*c^0.5;
x1=(-x1+apex_x)*c^0.5;
% Selection of the positive data, for right angle
k=1;
a=size(Xi_new);
if measuringangle==1
for i=1:a
if Xi_new(i)>=0 &Xi_new(i)<= x0% the data must be positive and lower than x0, the intersection point
Xi_new_pos_1(k)=Xi_new(i);
Zi_new_pos_1(k)=Zi_new(i);
k=k+1;
end
end
```

```
elseif measuringangle==2% selection of data needed to define the left angle
for i=1:a
if Xi_new(i)<=0 &Xi_new(i)>= x1
Xi_new_pos_3(k)=-Xi_new(i);
Zi_new_pos_3(k)=Zi_new(i);
k=k+1;
end
end
end
%condition true only for left angle
If measuringangle==2
lungh=length(Zi_new_pos_3);
k=lungh;
fori =1:lungh
Xi_new_pos_1(k)=Xi_new_pos_3(i);% store the coordinate, in order not to introduce other variables for the following functions
Zi_new_pos_1(k)=Zi_new_pos_3(i);
k=k-1;
end
end
% Defined the experimental points,b and c is possible to solve the set of ordinary differential equation
clear err
b=0.1292*2; % apex of curvature of first tentative
[err]=errorlaplace(b,c,Zi_new_pos_1,Xi_new_pos_1);% err is the output of the newfunctionerrorlaplace.m
%Optimization for Laplace
clear xopt
[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
%optimal value of b now bb,solve Laplace
bb=xopt;
[ x_ly_1,z_ly_1,Phi_ly_1]
=optimalaplace(bb,c,Xi_new_pos_1;Zi_new_pos_1);
% evaluation again of the coordinates needed to construct the theoretical profile, with the value of optimal b
% Plot the experimental profile and the theoretical one
```

```
linesize=3;
textsize=15;
plot(Xi_pos,Zi_pos,'b','LineWidth',linesize)%experimental data
hold on
plot(x_ly_1,z_ly_1,'g')%Laplace's data
set(gca,'YDir','reverse');% rotation of the graph
xlabel('value of x')
ylabel('value of z')
title('Fitting Drop')
hold off
% Output variables
rightangle=max(Phi_ly_1);% right angle[degrees]
height=max(z_ly_1);%height of the droplet [cm]
error=err;
valueapex=xopt;
%Import results into a txt.file
if measuringangle==1
fid=fopen('dataright.txt','a'); %open the data file
fprintf(fid,' %6.4f %6.4f %6.4f\n',angle,heigth,valueapex); %write theresults into the file
fclose(fid); %close the file
elseif measuringangle==2
fid=fopen('dataleft.txt','a'); %open the data file
fprintf(fid,' %6.4f %6.4f %6.4f\n',angle,heigth,valueapex); %write the values into the file
fclose(fid);
end
end
```

%B.1.3.1 Fitting trough an ellipse

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

```
s=s(2);
for i =1:s
if (psi/beta)>1% to select only positive roots
y_ellipse(i)=0;
elseif (x_(i)>=(gamma-alfa*(sqrt(1-(psi/beta).^2))) &&x_(i)<=(gamma+alfa*(sqrt(1-(psi/beta).^2))))
y_ellipse(i)=(beta*(sqrt(1-((x_(i)-gamma)/alfa).^2))+psi);% definition of the ordinata for ellipse
else
y_ellipse(i)=0;
end
end
%Evaluation of the error,as the difference between the ordinata of the two functions, the drop profile and ellipse
for i=1:s
res(i)=(y_(i)-y_ellipse(i)).^2;
end
%sum the errors
err=sum(res);
end
```

%B.1.3.2 Optimization ellipse

```
% Reference to the function optimalellipse.m, has been constructed the ellipse with the optimal combination of parameters
function[yellipse,xellipse]=optimalellipse(parameters,x_,y_)
alfa=parameters(1);
beta=parameters(2);
gamma=parameters(3);
psi=parameters(4);
s=size(x_);
s=s(2);
fori =1:s
if (psi/beta)>1
yellipse(i)=0;
elseif (x_(i)>= (gamma-alfa*(sqrt(1-(psi/beta).^2))) && x_(i)<=(gamma+alfa*(sqrt(1-(psi/beta).^2))))
yellipse(i)=(beta*(sqrt(1-((x_(i)-gamma)/alfa).^2))+psi);
else
yellipse(i)=0;
```

```
end
xellipse(i)=x_(i);end
```

%B.1.3.3 Laplace equation

```
% LAPLACE defines the ordinary differential equations to be solved.
% z=drop height
% x=distance from axis to drop interface
% phi=contact angle
% 1/b=radius of curvature at apex
% s=arc length
% NON−DIMENSIONALIZE Z,X,S,B USING C^(1/2)
% B=b*c^(1/2)
% X=x*c^(1/2)
% Z=z*c^(1/2)
% S=s*c^(1/2)
%.No need to define X,Z,S for equations
% Z=y(1); Z'=dy(1); Z' is with respect to S
% X=y(2); X'=dy(2); X' is with respect to S
% phi=y(3); phi'=dy(3); phi' is with respect to S
% Z'=sin(phi)
% X'=cos(phi)
% phi'=2/B+Z−(sin(phi)/X)
function [dy]=laplace(s,y,b,c)
dy = zeros(3,1); % a column vector
B=b*c^.5; % non-dimensionalized curvature at apex
dy(1)=sin(y(3));
dy(2)=cos(y(3));
dy(3)=(2/B)+y(1)-(sin(y(3))/y(2));
end
```

%B.1.3.4 Error function for b

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

```
b=max(Zi_new_pos_1);
a=size(z_ly);
for i=1:a
if z_ly(i)<b % selection of the points considering the maximum of the experimental data
z_ly_1(k)=z_ly(i);
x_ly_1(k)=x_ly(i);
k=k+1;
end
end
f=size(x_ly_1);
f=f(2);
%Comparison between only selected  points
primox=x_ly(1);
primoz=z_ly(1);
mediox=x_ly(round(f/2));
medioz=z_ly(round(f/2));
finalex=x_ly(f);
finalez=z_ly(f);
s=round(f/2);
secondox=x_ly(round(f-s/2));%from the basis to the middle point
secondoz=z_ly(round(f-s/2));
%fifth point
quintox=x_ly(round(s/2));
quintoz=z_ly(round(s/2));
%sixth point
met=round(s/2);
sestox=x_ly(round(f-s/2));
sestoz=z_ly(round(f-s/2));
%seventh point
sett=round(met/2);
settimox=x_ly(round(f-sett/2));
settimoz=z_ly(round(f-sett/2));
%eight (chosen this value because is to close to the point of interest)
ottavox=x_ly(f-22);
ottavoz=z_ly(f-22);
 %selection the same points but using experimental data
d=size(Xi_new_pos_1);
```

```
d=d(2);
primox1=Xi_new_pos_1(d);
primoz1=Zi_new_pos_1(d);
mediox1=Xi_new_pos_1(round(d/2));
medioz1=Zi_new_pos_1(round(d/2));
finalex1=Xi_new_pos_1(1);
finalez1=Zi_new_pos_1(1);
e=round(d/2);
secondox1=Xi_new_pos_1(round(e/2));
secondoz1=Zi_new_pos_1(round(e/2));
%fifth point
quintox1=Xi_new_pos_1(round(d-e/2));
quintoz1=Zi_new_pos_1(round(d-e/2));
%sixth point
mes=round(e/2);
sestox1=Xi_new_pos_1(round(mes/2));
sestoz1=Zi_new_pos_1(round(mes/2));
setts=(mes/2);
settimox1=Xi_new_pos_1(round(setts/2));
settimoz1=Zi_new_pos_1(round(setts/2));
ottavox1=Xi_new_pos_1(22);
ottavoz1=Zi_new_pos_1(22);
%evaluation of  error
xmax=Xi_new_pos_1(1);%define the maximum of data
%parameters that are important to define the error
eps=10^(-3);
a=1;
%error calculated as the distance between the experimental point and the one obtained from Laplace,the error is weighted
res1=(0.5)*(1/((abs(primox1-xmax))^a+eps))*((primox-primox1)^2+(primoz-primoz1)^2);
res2=(0.5)*(1/((abs(mediox1-xmax))^a+eps))*((mediox-mediox1)^2+(medioz-medioz1)^2);
res3=(0.5)*(1/((abs(finalex1-xmax))^a+eps))*((finalex-finalex1)^2+(finalez-finalez1)^2);
res4=(0.5)*(1/((abs(secondox1-xmax))^a+eps))*((secondox-secondox1)^2+(secondoz-secondoz1)^2);
res5=(0.5)*(1/((abs(quintox1-xmax))^a+eps))*((quintox-quintox1)^2+(quintoz-quintoz1)^2);
```

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

%B.1.3.5 Optimization Laplace

```
%The function optimalaplace.m is used in order to construct the theoretical profile starting with the optimal value of b
S_span=(0:.001:1);
[S,Y]=ode45(@laplace,S_span,[0 1e-100 0],[],bb,c);
x_ly(:,1)=Y(:,2);
z_ly(:,1)=Y(:,1);
S_ly(:,1)=S(:,1);
Phi_ly(:,1)=Y(:,3)*(180/pi);
k=1;
b=max(Zi_new_pos_1);
a=size(z_ly);
fori=1:a
ifz_ly(i)<b
Phi_ly_1(k)=Phi_ly(i);
z_ly_1(k)=z_ly(i);
x_ly_1(k)=x_ly(i);
k=k+1;
end
end
end
```

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