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Study on Surface Tension and Evaporation Rate of Human Saliva, Saline, and Water Droplets

Tian Zhang

Thesis submitted to the
College of Engineering and Mineral Resources
at
West Virginia University

In partial fulfillment of the requirements for the degree of

Master of Science

in

Mechanical Engineering

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ABSTRACT

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Tian Zhang

Cough, sometimes shedding plenty of germs and virus, is the human body's way of cleaning the breathing passages. The virus and germs spread rapidly through ambient air among humans and may cause infection. To reduce ultimately the infections caused by the germs and virus contained in human saliva droplets, it is necessary to understand the vaporization process of human saliva and its role on virus transmission. Virus-laden droplets, shed by an infected person through coughing and sneezing, evaporate until becoming droplet nuclei which will remain airborne for a long time and can infect other people. In other words, evaporation rate is an important factor affecting the transmission of virus and germ contained in human saliva. Accordingly, the present research focuses the evaporation of human saliva droplets, the carriers of virus. Experiments and numerical methods are utilized in this research to study surface tension and evaporation rate. In order to determine which component influences the surface tension and evaporation rate of droplet, different solutions are evaluated. Capillary tubes and a high performance camera are used for measuring the surface tension of these solutions. Evaporation measurements were carried out by taking pictures of droplets hanging vertically from a thin needle or laying on a flat surface. These images were later post-processed using an in-house developed Matlab code to obtain the evaporation rate. A more general evaporation equation was derived to determine numerically the evaporation rate of the different solutions and then used to analyze the evaporation process of multi-component droplets. Eventually, the numerical results compare

reasonably well with the experimental measurements. These findings will help understand the role of temperature and relative humidity of ambient air in virus transmission.

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Nomenclature

A	surface area
c_p	specific heat at constant pressure
D_v	diffusivity of water vapor in air
D_0	Initial Diameter
d	droplet diameter
e	pressure
e_{sat}	saturation vapor pressure over a pure, flat water surface
e_v	partial vapor pressure
$e_{v,0}$	initial vapor pressure of jet
$e_{v,\infty}$	vapor pressure of the ambient
g	acceleration due to gravity
h	height of the liquids in a capillary tube
k_a'	modified thermal conductivity of air
L_v	latent heat of vaporization of water
M	molecular weight
M_s	molecular weight of solute
m_N	mass of the solid components
m_s	mass of solute
R	universal gas constant
Re_r	Reynolds number based on the relative speed between the droplet and the carrier gas
RH	relative humidity
r	droplet radius
r_N	diameter of the nuclei after evaporation
Sc	Schmidt number
Sh	Sherwood number
T	instantaneous droplet temperature
T_∞	ambient air temperature
T_d	droplet temperature
t	droplet evaporation time

Greek Symbols

Φ_s	practical osmotic coefficient
θ	contact angle
ν	number of ions into which a salt molecule dissociates
ρ	density of liquids
ρ_A	density of specie A
ρ_s	mixture density
ρ_w	water density
σ	surface tension
σ_w	surface tension of water to the air
σ_{sw}	surface tension of salt water solution to the air
ω_A	mass fraction of specie A
$\omega_{A,\infty}$	mass fraction of specie A in the free stream
$\omega_{A,s}$	mass fraction of specie A at the droplet surface

Chapter 1: Introduction

1.1 Importance of droplets on the transmission of infectious diseases

Influenza virus affects millions of people every year (The New York Times, 2009). According to the World Health Organization (WHO), more than 16,455 people died and millions of people were affected in 2009 from influenza H1N1 (Swine flu) (Centers for Disease Control and Prevention - CDC, 2009). More research should be done to avoid and restrain the spread of viruses and germs, and thereafter, less people will be affected and killed by influenza. According to the CDC, avian influenza is contagious among birds (i.e., chickens, ducks, and turkeys) and can make some domesticated birds sick and die. Infected birds secrete influenza virus in their saliva, nasal secretions, and feces. Contacting with those contaminated secretions or excretions, some of susceptible birds might be infected (CDC, 2009). Although, typically these viruses do not affect human beings and there is no risk for us; there are increasing confirmed cases of human infection from several subtypes of avian influenza infection appeared increasingly (CDC, 2009). Therefore, the research on the control of the influenza virus is a matter of great urgency.

Among the paths of virus transmissions, the droplets generated by cough are important path. The breathing flow may transit the contagious secretion from the human body to the environment (Weber & Stilianakis, 2008). That is to say, the viruses and the germs from others might be transmitted into one's body by breathing and one can also expel viruses and germs to the environment. When people cough or sneeze, human saliva droplets will be sprayed; therefore, the human saliva is an important carrier of the influenza virus and should be studied. Additionally, there are millions of droplets included in a cough or sneeze (Duguid, 1946), and the transmission of the virus will happen when a cough or sneeze reaches another person. The

temperature, salinity and the constituents of the droplet are the properties that determine the droplet characteristics (i.e., surface tension, evaporation rate) of the droplets. In order to significantly reduce the transmission of the infectious virus by airborne droplets, the droplet characteristics should be understood.

There are several ways of transmission of virus and germs: (1) Direct contact with infected individuals; (2) Indirect contact with contaminated objects; (3) Inhalation of virus-laden aerosols; (4) inhalation or contact with large droplets. Considering the point of indirect contact with contaminated objects, those droplets (Diameter $> 5\mu\text{m}$) are the important source of infection, because they can travel and reach up to 2m and fall on the objects and contaminate them. Hence, in this research, comparatively large droplets (diameter up to 1mm) are studied, while small droplets (diameter $< 0.5\text{mm}$) are not included in the research.

1.2 Effect of droplet properties on evaporation

Viruses are shed by an infected person through coughing and sneezing and the water in the droplets of the cough and sneeze starts to evaporate. In case the saliva evaporates speedily, the droplets will remain airborne and not fall down to the ground. Anyone passing by and inhaling these droplets may be infected. Evaporation is important because it reduces the droplet diameter, and therefore the time that the droplets remain airborne. A water droplet of 0.17mm diameter, if it is generated by cough or sneeze in dry air (relative humidity = 0), the droplet will fall 2m in 3s, and if the surrounding air is not dry and the evaporation is slower, the droplet will settle slower (Wells, 1934). Furthermore, Nicas et al. (2005) also commented that evaporation process also affected the final size of the droplet. In this case, the evaporation is important, because it determines how fast the droplet settles and what the final size of the droplet is,. Therefore, the

droplet evaporation is an important factor which can influence the influenza transmission, and it is considered the main topic in this research. Generally, the evaporation rate of droplet is affected significantly by the droplet properties (e.g., surface tension, latent heat, salinity), and surrounding environment conditions (e.g., temperature, relative humidity, and wind velocity). This study will focus on how the droplet constituents and the environmental conditions influence the evaporation rate of water, saline, and human saliva droplets.

1.3 Literature review

Extensive experiments of water droplet, salt water droplet, and human saliva droplet have been conducted during the last decades. Investigation of the evaporation (Ranz & Marchall, 1952a) of distilled water droplet was examined based on the energy and mass transfer at low Reynolds numbers. Independent correlations of heat and mass transfer rates were obtained by measuring the drop temperatures measured with 0.127mm thermocouples. The diameter of the drops ranged from 0.06 to 0.11 cm. The experiment was performed in still dry air under the environmental temperature of 24.9°C and the temperature of the droplet was 9.11°C. In the experiment, photomicrographs were taken when the droplet was held by a feed capillary with a 0.127mm manganin-constantan thermo element junction at its center. According to their results, a 0.1cm diameter water droplet would take about 780 seconds to evaporate under those environmental conditions. Also, the results show that the results predicted by their model agreed well with experimental data.

Moyle et al. (2006) investigated the evaporation of small diameter (from 36µm to 50µm) water droplets. An electrodynamics particle trap was utilized to examine the evaporation of individual

high-purity water droplets, diameter ranged from 15 to 50 microns. The properties of the gaseous environment were: temperature around -43°C, dew point temperature around -33°C under the pressure around 59.2kpa. In this study, according to the information provided in that table, the relative humidity the environment around each droplet was calculated by using Magnus-Tetens approximation (Redmond, 2007) and it is 36%. In the theoretical analysis, the mass rate of change of a water droplet in a steady state vapor field (Pruppacher & Klett, 1978) was used to predict the diameter change with time. The results obtained from the experiments and the theoretical model show that the small water droplet evaporation can be predicted by using that numerical method.

Pyung et al. (1968) performed measurements of water droplet evaporation rates. In these experiments, water droplets were supported by two methods: a 0.18mm diameter Fenwal thermistor and a 40-μm diameter glass fiber with a beaded tip. A microscope was used for the photographic records. The results agreed with the quasi-stationary prediction from Maxwell's treatment (Fuks, 1959) that the rate of change of the evaporating droplet diameter should be inversely proportional to the droplet diameter (Equation 1):

$$\frac{dm}{dt} = -4\pi D_v (C_0 - C_\infty) \quad (1)$$

where m is the mass of the droplet, t is time, r is the radius of the drop, D_v is the diffusion coefficient of the water in air, C_0 is the saturated vapor concentration at the surface of the droplet, and C_∞ is the ambient vapor concentration.

John Redrow (2009) developed a numerical model for the evaporation of human saliva droplets expelled by a cough or sneeze. Also, he developed a model to simulate the transport of a sputum

droplet within a jet of air, representing a human cough. FLUENT was used to perform simulations of an experimental setup at the Morgantown NIOSH facility. A prediction of a human producing multiple, consecutive coughs within this room was simulated through the use of FLUENT, as well. In these simulations, small particles were injected into the room by the source of the cough, and their trajectories were tracked all the time. The calculated particle dispersion within the room was then compared to experimental results. In the experiment, the author is focusing more on the moving saliva droplet, and the droplet sizes ranged from 1.5 to 1500 μm . And then the droplet size should be very small (ranged from 1.5 to 1500 μm). In the first part of the study, it was proven by John Redrow to be quite accurate at predicting the properties of binary aqueous solution droplets containing either sodium chloride, glucose, or bovine serum albumin, but for ternary or higher order solutions, the result predicted does not match with experiment results. In the second part of the study, the transmission of the droplets generated by cough within a room was simulated.

Chapter 2: Measurement of Surface Tension

In this chapter, the methodology of performing the measurement of surface tension is introduced, including the measured liquids, equipment, and procedure of measurement in the experiment. Afterwards, the results and discussion are provided.

2.1 Methodology

2.1.1 Equipment

Table 2.1 shows all the equipment used in these measurements. As showing in Table 2.1, electrical balance was used to measure the mass of water, salt, etc; Tencor Alpha-Step 200 was used to measure the thickness; Finnipipette II was used to measure the volume of liquid; Canon camera, with Tokina lense, was used to take images; capillaries were used in the measurement of surface tension.

Table 2. 1. Equipments used in the measurement

Equipment	Range	Resolution	Manufacturer
Electrical balance - Adventurer ^{TM} Pro AV264	0-100g	0.001g	OHAUS, Pine Brook, New Jersey, USA
Electrical balance - Adventurer ^{TM} Pro AV114C	0-10g	0.001g	OHAUS, Pine Brook, New Jersey, USA
Tencor Alpha-Step 200	$\pm 160 \mu\text{m}$	0.015 μm	KLA-Tencor, Milpitas, California, U.S.A.
Finnipipette II	1-5mL	0.01mL	Fisherbrand, Pittsburgh, Pennsylvania, U.S.
Canon EOS 450D camera	N/A	N/A	Canon, Ōta, Tokyo, Japan
Tokina AT-X 100mm f/2.8 PRO D Macro Lens	N/A	N/A	Tokina, Tokyo, Japan
Capillary	N/A	N/A	Fisherbrand, Pittsburgh, Pennsylvania, U.S.

There are two kinds of capillaries in the experiment. The red marked tube has an inside diameter (I.D.) of 1.12 mm and an outside diameter (O.D.) of 1.47 mm. The yellow marked tube has an inside diameter of 0.96 mm and an outside diameter of 1.38mm. All of them are made of glass. When the capillary is inserted into water, there will be an “up-hill” (against the force of gravity) liquid level, and which is called “Capillary Phenomenon” (Batchelor, 2000). Figure 2.1 and 2.2 show the capillary phenomenon. Capillary tube is inserted to the solution, and there is a liquid column rising up.

Figure 2. 1 Surface Tension Measurement: Red Tube I.D. = 1.12mm, O.D. = 1.47mm

Figure 2. 2 Surface Tension Measurement: Yellow Tube I.D. = 0.96mm, O.D. = 1.38mm

Other devices were utilized during the measurements, such as beakers, iron supports, microinjector (1-10 μ L), etc.

2.1.2 Liquids to be measured

2.1.2.1 Compound solutions

Because of the surface tension is an important factor in droplet evaporation, as showing the equation 2.1, the surface tension of different liquids was measured. In order to have a more comprehensive research on surface tension influence on evaporation, many liquids were used in the measurement. These liquids included distilled water, tap water, 0.3% NaCl water solution, 0.6% NaCl water solution, 0.9% NaCl water solution, 0.6% glucose water solution, 0.9% glucose water solution, 5% milk water solution, 10% milk water solution, brewed coffee, and human saliva.

$$\sigma = \frac{h\rho g \cdot r}{2 \cos \theta} \quad (2.1)$$

where σ is the surface tension in [N/m], h is the height of the liquids in [m], ρ is density of liquids in [kg/m³], g is the acceleration of gravity in [m/s²], and r is the inner radius of the tube in [m], and θ is the contact angle.

2.1.2.2 Preparation of the liquids

The three different concentrations of salt water solutions were obtained by measuring the masses of pure solid NaCl and distilled water. For instance, to compound 0.3% NaCl solution, the procedure is as follows:

1. Calculate the mass of NaCl and distilled water (Table 2.2);
2. Put a piece of clean dry paper on the pallet of the *electrical balance*, set the balance to zero, and use the *spatula* to fill the calculated mass of salt on the paper, and put the salt into a beaker;
3. Lay a clean empty beaker on the pallet, set the balance to zero, and fill it with the calculated mass of distilled water,
4. Pour the water into the beaker which contains the salt, and mix the water and salt with glass rod gently, and
5. Repeat the same procedure to obtain the other two NaCl water solutions.

Table 2. 2 Measured mass of water and NaCl for three concentrations of NaCl water solutions

Mass	NaCl [g]	Distilled Water [g]
0.3% NaCl Water Solution	0.1501	49.8509
0.6% NaCl Water Solution	0.3002	49.7009
0.9% NaCl Water Solution	0.4502	49.5501

The glucose water solutions are obtained with the same procedure used before but with different concentrations (Table 2.3).

Table 2. 3 Measured data of mass of water and glucose for two concentrations of glucose water solutions

Mass	Glucose [g]	Distilled Water [g]
0.6% Glucose Water Solution	0.3001	49.7008
0.9% Glucose Water Solution	0.4503	49.5505

Milk water solutions were made from 0.02% fat milk. The procedure to obtain it is the same as the one used before, and the measured mass of milk is in Table 2.4.

Table 2. 4 Measured data of mass of water and milk of the two concentrations of milk water solutions

Mass	0.02% Fat Milk [g]	Distilled Water [g]
5% milk Water Solution	2.5001	47.5003
10% milk Water Solution	5.0003	45.0009

2.1.2.3 Densities of solutions

Density values would be used in the surface tension calculation. After collecting all the solutions, density of each liquid should be measured. The density of distilled water is assumed to be the same as the density of pure water under normal temperature and pressure (20°C and 1atm, respectively) (Efunda, 2011). During the experiments, the temperature and pressure are kept well at 20-23°C and 1atm, respectively.

The density of the tap water is obtained as the same temperature and pressure as the distilled water (SImetric, 2010).

Three methods were used to obtain the densities of NaCl solutions. One method is by calculation. The second method is to measure the mass and volume of the three NaCl solutions by taking 10 times measurements, the density value can be calculated as an mean value density. In this method, V is fixed and set to 2 mL. The procedure is as follows:

1. Use Finnipipette II 1-5mL (Fisherbrand, Pittsburgh, Pennsylvania, U.S.) to measure 2 mL of liquids;
2. Lay a beaker onto the pallet of the electrical balance, set the balance to zero;
3. Put the liquid into the beaker, and read the mass
4. Repeat this process 10 times (Table 2.5);
5. Calculate the mean mass

Table 2. 5 Measured mass data of three concentrations of NaCl solutions with fixed volume 2mL

Mass	0.3% NaCl solution [g]	0.6% NaCl solution [g]	0.9% NaCl solution [g]
1	2.0014	2.0095	2.0126
2	2.0029	2.0074	2.0130
3	2.0032	2.0063	2.0140
4	2.0040	2.0079	2.0129
5	2.0036	2.0069	2.0115
6	2.0031	2.0075	2.0136
7	2.0028	2.0085	2.0143
8	2.0042	2.0090	2.0150
9	2.0036	2.0080	2.0127
10	2.0035	2.0096	2.0131
Mean	2.0032	2.0081	2.0133

The final method is from “The Engineering Toolbox”. It offers a relationship between the concentration of NaCl solutions and their densities (Fig. 2.3) (EngineeringToolBox, 2009)

Figure 2. 3 Density changing with concentration of NaCl

A function of density and concentration is calculated, which is:

$$\rho = 7.84c + 1000 \quad (2.2)$$

Where c is the concentration and ρ is the density of the NaCl solution. Then the density of any NaCl solution can be obtained as long as the concentration is known.

The other reference is a calculator developed by CSGNetwork (CSG Method), University of Michigan, and NOAA (NOAA, 2010). The calculator can compute the NaCl solution density if the value of temperature and concentration are given (NOAA, 2010)

Table 2.6 shows the results of the three methods.

Table 2. 6 Results of densities of NaCl solutions of the three methods

Density [kg/m ³]	Method 1 (Calculation)	Method 2 (Measurement)	Method 3 (Function)	Method 4 (CSG Method)
0.3% NaCl solution	1001.20	1001.6	1002.35	999.85
0.6% NaCl solution	1004.23	1004.0	1004.70	1002.11
0.9% NaCl solution	1007.27	1006.6	1007.06	1004.37

From Table 2.6, the difference of density values of each method is small; since the result of method 2 was obtained by measurement, it was used in this thesis.

The densities of glucose water solutions are obtained by measurement, and the method is the same as used in the NaCl water solutions.

The densities of 0.02% fat milk water solutions were obtained by using equation:

$$\rho_{mixture} = \sum_{i=1}^n \rho_i \omega_i \quad (2.3)$$

where $\rho_{mixture}$ is the density of milk water solution; ρ_i is the density of each component in the solution, including 0.02% fat milk and distilled water; and ω_i is the mass fraction of each component. The density of 0.02% fat milk is 1,033 kg/m³ at 20 °C (Jones, 2002).

The density of brewed coffee was measured by the same procedure before, but the fixed volume was set to 5mL.

Two methods were used to obtain the density of human saliva. One is measurement, and the other one is calculation. The measured human saliva is collected between 9:00 AM to 11:00 AM as unstimulated whole saliva (Chiappin et al., 2007). The procedure is still the same as before.

The measured data is shown in Table 2.7.

Table 2. 7 Measured mass and calculated density of human saliva

Mass [g]	Density [g/cm ³]
2.0032	1.00160

1.9998	0.99990
2.0039	1.00195
2.0045	1.00225
2.0089	1.00445
2.0061	1.00305
2.0045	1.00225
1.9993	0.99965
2.0034	1.00170
2.0012	1.00060

From Table 2.7, the average value of density of human saliva can be calculated, which is 1001.73 kg/m³.

Human saliva contains many substances, including the major component water, inorganic salt components, organic components, etc. The mass fraction and density of each component have been obtained by some scientists before. These mass fractions are 99.5% water, 0.3% proteins, and 0.2% inorganic and trace substances (Schipper et al., 2007). These data were used in the calculation of human saliva density.

Some assumptions were made in this method. First, because trace substances constitute a very small part in human saliva, less than 1/10000, they were neglected in the calculation. Then, there are many kinds of inorganic ions in human saliva listed (Table 2.8) (Chiappin et al., 2007).

Table 2. 8 Mass concentration of inorganic components of human saliva

Inorganic components	Mole [mmol/L]	Concentration [mg/L]	Molecular weight [g/mol]
Na ⁺	5	115	23
K ⁺	22	860.2	39.1
Cl ⁻	15	532.5	35.5
Ca ²⁺	2.5	100	40
HCO ₃ ⁻	5	305	61
Mg ²⁺	0.2	4.8	24

NH_3^+	6	108	18

In order to calculate the density of human saliva, the density of each component should be known. Table 2.8 shows the amount of solvent of each substance, and according to those data, some solid substances were assumed when water evaporates completely. In Table 2.9, the amount of NaCl, KCl, MgCl_2 , and NH_4HCO_3 are listed by combining the ions in Table 2.8 in 1 mL human saliva. For instance, 5 mol of Na^+ was considered combined with 5 mol Cl^- , and then 5 mol sodium chloride was created.

Table 2. 9 Mole number in 1mL and density information of salts in human saliva

	Mole [mmol]	Density [kg/m^3]
NaCl	5	2165
KCl	10	1984
MgCl_2	0.2	2320
NH_4HCO_3	5	1586

After combining the anions with cations, there are still some cations remained. As for there are no more anions can be used to create substance, the rest of cations (i.e. 12mmol/L of K^+ , 2.5mmol/L of Ca^{2+} , etc.) were neglected.

Secondly, protein was another important substance in human saliva, taking up to 0.3% in human saliva (Chiappin et al., 2007). There were plenty of kinds of proteins in human saliva (Chiappin et al., 2007), but most of them had a very small amount and they were ignored here. The major components were shown in Table 2.10.

Table 2. 10 Major components of proteins in human saliva

	Concentration [mg/ml]	Mass in 1mL [mg]	Molecular Weight [g/mol]	Density [g/cm ³]
α -amylase	0.476	0.476	51000 ^[1]	1.25 ^[2]
Albumin	0.2	0.2	66438 ^[3]	1.202 ^[4]
Secretory-IgA	0.2298	0.2298	70000 ^[5]	1.145 ^[6]
Hystatin	1.19	1.19	926.09 ^[7]	1.26 ^[8]
Statherin	36	36	5379.59 ^[9]	Not Found
PRPs	0.621	0.621	35500 ^[10]	Not Found
Transferrin	58	58	80000 ^[11]	Not Found

[1] (WBC, 2010), [2] (Makkar et al., 2007), [3-4] (Bull, 1941), [5-6] (Tartakoff, 1982), [7] (Rxlist, 2008), [8] (Esser et al., 1979), [9] (Gururaja & Levine, 1996), [10] (Hegde et al., 2010), [11] (Roberts et al., 1966)

The density information of last three kinds of proteins was not found, and they were neglected in the calculation. Thus, all the substances which were used in the calculation had been introduced (Table 2.11).

Table 2. 11 Substances used in the calculation of density of 1 mL human saliva

	Density [kg/m ³]	Mole [mmol]	Molecular Weight [g/mol]	Mass [kg]	Volume [m ³]
NaCl	2165	5	58.5	0.000293	1.35E-07
KCl	1984	10	74.6	0.000746	3.76E-07
MgCl ₂	2320	0.2	95	0.000019	8.19E-09
NH ₄ HCO ₃	1586	5	79	0.000395	2.49E-07
α -amylase	1250	0.0078	51000	0.0003978	3.18E-07
Albumin	1202	0.003	66438	0.0002	1.66E-07
Secretory-IgA	1145	0.0033	70000	0.00023	2.01E-07
Hystatin	1260	1.285	926.09	0.00119	9.44E-07

Table 2.11 shows the densities, mole number and molecular weight of each component in 1mL of human saliva. The mass of each component can be calculated by the relationship:

$$m = n \cdot M \quad (2.4)$$

where m is the mass of each component, n is the mole number, and M is the molecular weight, which are all shown in Table 2.11.

After obtaining the volume and mass of each component in Table 2.11, the total volume of the inorganic components is $2.398\text{E-}06 \text{ m}^3$ and mass of the inorganic components of proteins 0.00347kg ; therefore, the density is 1446.99kg/m^3 . The total volume is the summation of the volume of all the solid components in Table 2.11. Similarly, the total mass is the summation of the mass of all the solid components in Table 2.11.

In order to validate the assumption and calculation of the solid part of density of human saliva, an experiment was performed. The procedure of the experiment was:

- Mark five pieces of glass; weigh these glasses by using Adventurer Pro AV114C (OHAUS, Pine Brook, New Jersey, USA)
- Inject human saliva droplet on the glass
- Warm up ($50\sim 60^\circ\text{C}$) the glass to let water in saliva evaporate more rapidly (less than 1 minute). Figure 2.4 shows the samples of human saliva solid part after the water evaporated.

Figure 2. 4 Samples of the human saliva solid part on glasses

- Weigh the mass of each again, then by subtracting the glass mass, the mass of solid part of humans saliva on each glass can be obtained;
- Then use Tencor Alpha-Step 200 ($\pm 160 \mu\text{m}$ height range) to measure the height of the solid part of saliva on the glass
- Afterward, take pictures for each of the sample individually, and use Matlab program to analyze it and calculate the surface area.

Figure 2. 5 The sample of image analysis of surface area of the solid part

- By this time, the density of saliva solid part can be obtained, by knowing both mass and volume. Table 2.12 shows the calculation and results.

Table 2. 12 The measurement data and calculation of density of solid part of human saliva

Group*	Total Area [m ²]	Height [m]	Weight [kg]	Volume [m ³]	Density [kg/m ³]
2	4.01E-04	3.00E-06	1.50E-06	1.20E-09	1246.35
3	6.17E-04	1.35E-06	1.20E-06	8.31E-10	1443.74
4	3.32E-04	1.86E-06	1.00E-06	6.17E-10	1621.24
5	2.02E-04	4.58E-06	1.20E-06	9.26E-10	1296.22

* Group 1 seemed like an outlier and was deleted in the calculation

Take average value of the density in Table 2.12, the density of solid part in human saliva by measurement is 1401.88 kg/m³; compared to the result of calculation 1446.99 kg/m³, the difference is 3.12% which is not a high error.

After obtaining the density of the solid part of human saliva, water was taken into account and the total density of human saliva was calculated (Table 2.13).

Table 2. 13 Calculation of density of human saliva

	Mass fraction	Mass [kg]	Density [kg/m ³]	Volume [m ³]	Total Volume [m ³]	Final Density [kg/m ³]
Solids	0.005	0.00347	1446.99	Neglected	0.000692	1003.22
Water	0.995	0.691	998.2	0.000692		

Table 2. 14 Difference of human saliva density of the two methods

	Density [kg/m ³]	Error
Calculation	1003.22	0.15%
Measurement	1001.73	

The measurement density is mentioned in Table 2.7. From table 2.14, it can be observed that the error between the measurement and the calculation is small, so the measurement result of the density of human saliva was used in this study.

2.1.2.4 Procedure for measuring surface tension

The surface tension of the solutions was measured by placing the capillary tubes into those prepared liquids contained in the beakers. The capillary tubes was held by the iron support. After a while, due to the capillary effect, a rising liquid level inside of the capillary tubes can be observed. The height of the rising liquid h inside of the tube and the contact angle between the top liquid level and the inner tube wall θ can be obtained. High resolution pictures were taken for the whole system after the liquid level stabilized. Figures 2.6 was the sample of the measurement sets.

Figure 2. 6 Height of the liquid level system

After taking pictures, all of them are processed to provide h and θ for the calculation of surface tension.

2.1.2.5 Height in the tube

In order to guarantee the accuracy of the values of the height inside of the capillary tubes, Photoshop (Adobe Systems, Inc. San Jose, CA) was used to measure the pixel length of the inner diameter d_{inside_pixel} , outside diameter $d_{outside\_pixel}$, and the height between the higher liquid level and the lower liquid level h_{pixel} . The actual outside diameter $d_{outside}$ has been obtained by the slide caliper, and Equation 2.4 was used to compute the height h and the inner diameter d_{inside} :

$$\frac{d_{inside}}{d_{inside\_pixel}} = \frac{d_{outside}}{d_{outside\_pixel}} = \frac{h}{h_{pixel}} \quad (2.5)$$

2.1.2.6 Contact angle

The contact angle is the angle at which a liquid or vapor interface meets a solid surface (Muson et al., 1994). Two methods were used to measure the contact angle. One is using Matlab code to obtain the boundary of the meniscus, and using the boundary, the contact angle can be calculated; the other one is to measure it by using ruler The purpose to measure the contact angle by two ways is to have a comparison of the values obtained from each method to ensure the accuracy.

A Matlab code was written to obtain the meniscus edge of the fluid. Then, it can capture a boundary of the picture. An example (Figure 2.7) of attaining the boundary of one picture is as follows:

Figure 2. 7 Contact angle by Matlab: (a) Actual photo of the boundary, (b) Maniscus boundary obtained from Matlab

After capturing the boundary of the meniscus, two points at the boundary, either right or left side, were chosen, and the slope of the line between the two points can be calculated by using their coordinate value obtained by Matlab,. The slope is equal to $\tan(90-\theta)$, and the contact angle θ is calculated.

The measurements for distilled water, salt solutions, and human saliva have been repeated more than 5 times.

The second method is to measure the contact angle by hand. The contact angle boundary pictures were printed, and a ruler was used to get the slope of the meniscus near the wall. The slope is also equal to $\tan(90-\theta)$, and the contact angle θ is calculated.

2.1.3 Data Processing

The surface tension of each liquid can be calculated using the Equation 2.1.

2.2 Results and Discussion

Collecting all the values needed in Equation 2.1, the surface tension of each liquid can be calculated (Table 2.15).

Table 2. 15 Results of surface tension of each kind of liquid

Solutions	σ [N/m]
Distilled water	0.0692
0.3% Glucose ($C_6H_{12}O_6$)	0.0680
0.6% Glucose	0.0650
5% milk	0.0576
10% milk	0.0540
Brewed Coffee	0.0561
Tap water	0.0659
Saliva	0.0657
0.3% NaCl	0.0782
0.6% NaCl	0.0806
0.9% NaCl	0.0845

Figure 2.8 shows the surface tension of all the solutions measured. Some trends can be observed. As shown in Figure 2.8 the surface tension of the NaCl solution was found to increase with the NaCl concentration. This agreed with the result reported by (Lloyd Trefethen, 1969) which said that when some inorganic salts dissolved in water, the surface tension of the solution would increase. In addition, considering the sugar water solution, as the concentration increases, the surface tension will decrease. It has an opposite relationship between the concentration and surface tension with inorganic salts. It is also in agreement with the result published that when

some organic substances dissolved in water, the surface tension of water will decrease (Lindfore, 1924; Weissenborn, 2006). Furthermore, the more milk dissolved in water, the lower surface tension obtained. The surface tension of human saliva is comparable to that of tap water.

Figure 2. 8 Surface tension of each liquid

Chapter 3: Measurement of Evaporation Rate

3.1 Experimental Set-up and Procedure

Experiments were performed to acquire the characteristics of droplet evaporation. The solutions measured included distilled water, tap water, NaCl with different concentrations, and human saliva.

The NaCl water droplets were attained from three different concentrations of NaCl water solutions, 0.3% NaCl water solution, 0.6% NaCl water solution, 0.9% NaCl water solution, which are made by the same method as the solutions used in the surface tension measurements. The human saliva droplet is from unstimulated human saliva (Chiappin et al., 2007).

The procedure for the measurement of the evaporation rate of distilled water droplets is explained in the following lines. The water sample has to be placed in the experimental environment for more than 30 minutes, in order to obtain the same temperature of the environment. A calculation (Appendix I) has been done to prove that 30 minutes is long enough to ensure the temperatures are the same. Temperature and relative humidity of the surrounding environment are monitored by the hygrometer (Meade Instruments Corp., Irvine, CA, USA) during the entire measurement. Wind velocity has a significant effect on the evaporation rate, and it is measured by a hot wire thermo-anemometer (Extech Instruments Corporation, Waltham, MA, USA). Thereafter,

1. The temperature, relative humidity and the wind velocity were recorded at the beginning of the experiment, and the solutions to be studied would be placed in the experimental environmental for more than half an hour, sometimes, with a cover on top of the beakers;

2. The microinjector (1-10 μ L) (Figure 3.1) is used to ingest some water;

Figure 3. 1 Scales on microinjector

3. Inject 1 μ L water approximately by subtracting the scales on the microinjector;
4. Move the water droplet down to the middle of the needle on the microinjector by slightly shaking, or inject a droplet and lie it on a flat plate;
5. If the droplet is held by the needle, hold it with the iron support vertically;
6. Taking pictures of the droplet every 30 seconds during the whole evaporation process;
7. Record the temperature, relative humidity and wind velocity at the end of the experiment, and if the difference between the initial and final droplet is small then the conditions can be considered as constants;

The 4^d and 5th step should be done as soon as possible to decrease the amount of water lost by evaporation. In order to obtain high quality pictures of the evaporation process, the illumination condition can easily influence the result; there will be a fluctuation of the illumination intensity shown in the pictures even a person just passing by, and afterward the results obtained from Matlab would be influenced. Therefore, the illumination intensity should be exactly the same during the entire process. In this research, in order to reduce the influence of the fluctuation of illumination intensity, a photo studio (Merax, City of Industry, CA, USA) was used to cover the droplet.

Repeat the same procedure to all the other liquids to obtain the pictures. Figure 3.2 shows how the experiment is designed.

Figure 3. 2 Photo studio used in the experiment of evaporation rate

3.2 Image Analysis

A Matlab code is programmed to analyze the pictures of the evaporation attained previously, computing the volume and surface area of the droplet changing with time. The Matlab program zoomed in the droplet on the photos continuously and changed the photos to binary form (Figures 3.3 and 3.4), only containing black and white.

Figure 3. 3 Pictures of droplet on the needle: (a) Photo of droplet on the needle, (b) Binary photo obtained from program

Figure 3. 4 Pictures of droplet on the surface: (a) Photo of droplet on the needle, (b) Binary photo obtained from program

In the binary photo, the boundary of the droplet can be captured. Considering the droplet on the needle is symmetric approximately by the centerline of the needle, the left part is used in the calculation of its volume and surface area.

The surface area of a sphere is shown in Equation 3.1:

$$A = 4\pi r^2 = \pi d^2 \quad (3.1)$$

and for a semi-sphere, the surface area is shown in Equation 3.2:

$$A = 2\pi r^2 = \frac{1}{2}\pi d^2 \quad (3.2)$$

where A stands for the surface area and d is the diameter of the droplet.

The program performed this calculation procedure for all the pictures and showed the evaporation of a single droplet. A video showing the entire evaporation process of the droplet was then created. Eventually, the evaporation rate can be calculated. For example, Figure 3.5 shows the experimental result of evaporation rate of distilled water droplet measured at ambient temperature of 22.6°C and relative humidity of 48%. It is showing that the evaporation rate is almost a straight line.

Figure 3. 5 The experimental result of evaporation rate distilled water droplet: Surface area vs. Time

Figure 3.6 shows the Experimental results of 0.3% NaCl water solution droplet, 0.6% NaCl water solution droplet, 0.9% NaCl water solution droplet, and human saliva droplet evaporation under 13.5°C and relative humidity of 33%;

Figure 3. 6 Experimental results: saline water and human saliva droplets evaporation: Surface area vs. Time

In order to ensure the experiment is reliable, there are several groups of evaporation performed for each liquid. Figure 3.10 shows the experimental result of evaporation of NaCl water solution droplets under temperature around 34.5°C and relative humidity around 26%.

Considering Figure 3.5 to Figure 3.6, there are some small fluctuations throughout the experimental result of evaporation. However, generally, it can be observed that the surface area of droplet is changing linearly with time.

Figure 3.7 shows the experimental evaporation results of droplets of different NaCl water solutions. The 0.3% NaCl water solution droplet evaporates slightly faster than the 0.6% and 0.9% NaCl water solution droplets.

Figure 3. 7 The experimental result of evaporation of NaCl water solution droplets: Surface area [mm²] vs. Time [s]

Figure 3.8 shows the experimental result of evaporation of human saliva droplets under temperature around 23°C and relative humidity around 30%.

Figure 3. 8 The experimental result of evaporation of human saliva droplets: Surface area [mm²] vs. Time [s]

From Figure 3.7 and 3.8, the evaporation rates of various solutions are different. Besides, from Figure 3.11, under same environmental conditions, it can be observed that the evaporation of different human saliva droplets have the same evaporation rate.

Figure 3.9 shows the experimental results of evaporation of human saliva droplets under different environmental temperature and relative humidity. It shows that when temperature increases, the evaporation rate will increase, as shown, and when relative humidity decreases, the evaporation rate will increase.

Figure 3. 9 Experimental results of semi-sphere Human saliva Droplets evaporation under different environmental temperature and relative humidity: Surface area [mm²] vs. Time [s]

Chapter 4: Mathematical Model of Evaporation

Mathematical Model

According to Fick's law, the mass flux at the surface of an evaporating or condensing droplet in a binary mixture is:

$$\rho_s \omega = -D_v \frac{\partial \rho_A}{\partial n} \quad (4.1)$$

where n is the coordinate normal to and away from the surface, ρ_A is the mass density of species A, ρ_s is the mixture density, D_v is the diffusion coefficient (Crowe et al., 1997). Then,

$$\rho_s \omega = -\rho_s D_v \frac{\partial (\rho_A / \rho_s)}{\partial n} = -\rho_s D_v \frac{\partial \omega_A}{\partial n} \quad (4.2)$$

where ω_A is the mass fraction of species A in the mixture (Crowe et al., 1997).

For a droplet of diameter d the gradient of mass fraction must be proportional to the mass fraction difference between the surface and the free stream and inversely proportional to the droplet diameter:

$$\rho_s \omega = -\rho_s D_v \frac{\partial \omega_A}{\partial n} \propto \rho_c D_v \frac{\omega_{A,s} - \omega_{A,\infty}}{d} \quad (4.3)$$

where $\omega_{A,s}$ is the mass fraction of species A at the droplet surface and $\omega_{A,\infty}$ in the free stream.

The density ρ_c is the representative density and may be the average density between the surface and the free stream (Crowe et al., 1997).

The droplet continuity equation states that the rate of change of droplet mass is the negative value of the mass efflux through the droplet surface,

$$\frac{dm}{dt} = -\rho_s \omega A \quad (4.4)$$

where A is the area of the droplet surface (Crowe et al., 1997).

Thus the rate of change of droplet mass should be proportional to

$$\frac{dm}{dt} \propto \pi d^2 \rho_c D_v \frac{\omega_{A,\infty} - \omega_{A,s}}{d} \quad (4.5)$$

The constant of proportionality is the Sherwood number so the equation becomes (Crowe et al., 1997).

$$\frac{dm}{dt} = Sh \pi d \rho_c D_v (\omega_{A,\infty} - \omega_{A,s}) \quad (4.6)$$

where Sh is Sherwood number (Crowe et al., 1997):

$$Sh = 2.0 + 0.6 \text{Re}_r^{0.5} \text{Sc}^{0.33} \quad (4.7)$$

where Re_r is the Reynolds number based on the relative speed between the droplet and the carrier gas,

$$\text{Re}_r = \frac{d |\mathbf{u} - \mathbf{v}|}{\nu} \quad (4.8)$$

Where $\mathbf{u}$ and $\mathbf{v}$ are the velocity of the continuous and dispersed phases, respectively, ν is the kinetic viscosity.

Sc is the Schmidt number defined by

$$\text{Sc} = \frac{\nu}{D_v} \quad (4.9)$$

The mass fraction terms:

$$\omega_{A,\infty} - \omega_{A,s} = \frac{\rho_{A,\infty} - \rho_{A,s}}{\rho_c} \quad (4.10)$$

where $\rho_{A,\infty}$ is the vapor density in free stream and $\rho_{A,s}$ is the density at droplet surface.

Then, equation (4.6) turns to:

$$\frac{dm}{dt} = 2Sh\pi r D_v (\rho_{A,\infty} - \rho_{A,s}) \quad (4.11)$$

The mass changing with time can be represented by:

$$\frac{dm}{dt} = \frac{d}{dt} \left(\rho_d \frac{\pi d^3}{6} \right) = \frac{\pi}{2} \rho_d d^2 \frac{dd}{dt} \quad (4.12)$$

Thus

$$\frac{\pi}{2} \rho_d d^2 \frac{dd}{dt} = 2Sh\pi r D_v (\rho_{A,\infty} - \rho_{A,s}) \quad (4.13)$$

where ρ_d is the droplet density. (Pruppacher & Klett, 1978)

From ideal gas law

$$\rho = \frac{eM}{RT} \quad (4.14)$$

where R is the universal gas constant, e is the atmosphere pressure.

Equation (4.11) becomes

$$\frac{dm}{dt} = \frac{2Sh\pi r D_v M_\omega}{R} \left(\frac{e_\infty}{T_\infty} - \frac{e_d}{T_d} \right) \quad (4.15)$$

where e_∞ is the vapor pressure in the free stream, e_d is the vapor pressure at droplet location, T_∞ is the temperature in the free stream and T_d is the droplet temperature.

Then,

$$r \frac{dr}{dt} = \frac{Sh D_v M_\omega}{2R \rho_d} \left(\frac{e_\infty}{T_\infty} - \frac{e_d}{T_d} \right) \quad (4.16)$$

An expression for the temperature T_d at the droplet surface can be obtained by considering the coupling of the rates of change of heat and mass through heat release (Pruppacher & Klett, 1978):

$$T_d = T_\infty + \frac{L_v \rho_d}{k'_a} r \frac{dr}{dt} \quad (4.17)$$

where L_v is the latent heat of evaporation, k'_a is the modified thermal conductivity (Crowe et al., 1997):

Let

$$\delta = \frac{L_v \rho_d}{T_\infty k'_a} r \frac{dr}{dt} \quad (4.18)$$

Then

$$\frac{T_d}{T_\infty} = 1 + \delta \quad (4.19)$$

Rewrite equation (4.16)

$$r \frac{dr}{dt} = \frac{ShD_v M_w}{2R\rho_d} \frac{e_{sat,w}(T_\infty)}{T_\infty} \left(\frac{e_\infty}{e_{sat,w}(T_\infty)} - \frac{e_d}{e_{sat,w}(T_\infty)} \frac{T_\infty}{T_a} \right) \quad (4.20)$$

where $e_{sat,w}(T_\infty)$ is the saturated vapor pressure at temperature T_∞ .

Relative humidity is defined as:

$$RH = \frac{e_\infty}{e_{sat,w}(T_\infty)} \quad (4.21)$$

and

$$\frac{e_d}{e_{sat,w}(T_\infty)} = \frac{e_d}{e_{sat,w}(T_d)} \cdot \frac{e_{sat,w}(T_d)}{e_{sat,w}(T_\infty)} = \exp \left[\frac{L_e M_w}{RT_\infty} \left(\frac{\delta}{1+\delta} \right) + \frac{2M_w \sigma_{s/a}}{RT_\infty (1+\delta) \rho_w a} - \frac{\nu \Phi_s M_w / M_s}{(4\pi a^3 \rho_d / 3) - m_s} \right] \quad (4.22)$$

where $\sigma_{s/a}$ is the surface tension, ρ_w is the water density, ν is number of ions into which a salt molecule dissociates, Φ_s is the practical osmotic coefficient, M_s is the molecular weight of salt and m_s is the mass of salt in the droplet (Pruppacher & Klett, 1978). Then, the general equation becomes:

$$r \frac{dr}{dt} = \frac{ShD_v M_w}{2R\rho_d} \frac{e_{sat,w}(T_\infty)}{T_\infty} \left\{ RH - \frac{1}{1+\delta} \exp \left[\frac{L_e M_w}{RT_\infty} \left(\frac{\delta}{1+\delta} \right) + \frac{2M_w \sigma_{s/a}}{RT_\infty (1+\delta) \rho_w r} - \frac{\nu \Phi_s M_w / M_s}{(4\pi r^3 \rho_d / 3) - m_s} \right] \right\} \quad (4.23)$$

Equation 4.22 is an equation which can solve binary solutions, but for the purposes we need a more general model that can solve for multiple component solutions. To modify equation (4.22), using an aqueous solution drop containing a solid insoluble substance (Pruppacher & Klett, 1978)

$$\frac{e_d}{e_{sat,w}} = \exp \left[\frac{2M_w \sigma_{s/a}}{RT \rho_w r} - \frac{v \Phi_s \varepsilon_m M_w \rho_N r_N^3}{M_s \rho_w (r^3 - r_N^3)} \right] \quad (4.24)$$

where $\varepsilon_m \equiv m_s/m_N$, m_N is the mass of the solid components, r_N is the diameter of the nuclei after evaporation.

Replacing the term shown in equation (4.22) in equation (4.23):

$$r \frac{dr}{dt} = \underbrace{\frac{Sh D_v M_w e_{sat,w}(T_\infty)}{2R \rho_d T_\infty}}_{\text{Diffusion Term}} \left\{ RH - \frac{1}{1+\delta} \exp \left[\underbrace{\frac{L_e M_w}{RT_\infty} \left(\frac{\delta}{1+\delta} \right)}_{\text{Latent Heat Term}} + \underbrace{\frac{2M_w \sigma_{s/a}}{RT_\infty (1+\delta) \rho_w r}}_{\text{Surface Tension Influence}} - \underbrace{\frac{M_w \rho_N r_N^3}{\rho_d (r^3 - r_N^3)} \sum_y \frac{\nu_y \Phi_y \varepsilon_y}{M_y}}_{\text{Solute Influence}} \right] \right\} \quad (4.25)$$

A Matlab program was developed by using the mathematical model of equation (4.25).

To solve Equation 4.23, the valuables in the equation should be specified.

$$D_{v,original} = 0.211 \left(\frac{T_d}{T_0} \right)^{1.94} \left(\frac{P_0}{P} \right); \text{ (Pruppacher \& Klett, 1978)}$$

The original equation is only valid for the distances greater than the ‘vapor jump’ length Δ_v ($\Delta_v \approx \lambda$ mean free path) which is the average distance covered by a moving particle between successive impacts) from the drop surface. For the region $r \leq r_i \leq r + \Delta_v$, we need to consider the gas kinetic expressions and the original equation needs to be

modified. $D_v = \frac{D_{v,original}}{\left[\frac{r}{r + 5e-8} + \frac{D_{v,original}}{r * 0.002} \left(\frac{2\pi}{RT_d} \right)^{0.5} \right]}$ (Pruppacher & Klett, 1978); this equation is used

to calculate in the Matlab code;

$$e_{sat,w} = 6.1121(1.0007 + 3.46 \times 10^{-6} P) \exp\left(\frac{17.502T_d}{240.97 + T_d}\right) \text{ (Andreas, 2005), and it is used in the}$$

Matlab code;

$$c_p = 1005.60 + 0.017211T_d + 0.000392T_d \text{ (Andreas, 2005);}$$

$$L_v = (25.00 - 0.02274 * T_c) * 10^5 \text{ (Andreas, 2005);}$$

$$K_{a,original} = 0.02411(1 + 3.309e - 3T_d - 1.441e - 6 \times T_d^2) \text{ (Andreas, 2005);}$$

$$K_a = \frac{K_{a,original}}{\left[\frac{r}{r + 2.16e - 7} + \frac{K_{a,original}}{r \times 0.7 * \rho \times c_p} \left(\frac{2\pi M_a}{RT_a} \right)^{0.5} \right]} \text{ (Pruppacher & Klett, 1978);}$$

The number of ions into which a salt molecule dissociates: $\nu = 2$;

$$\Phi_s = 0.0055 \left(\frac{m_{salt}}{M_s} \right)^2 + 0.028 \left(\frac{m_{salt}}{M_s} \right) + 0.9128 \text{ (Pruppacher & Klett, 1978);}$$

$$\sigma_w = 0.2358 \left(\frac{374 - T_d}{647.15} \right)^{1.256} \left(1 - 0.625 \left(\frac{374 - T_d}{647.15} \right) \right) \text{ (Andreas, 2005);}$$

$$\sigma_{sw} \cong \sigma_w$$

Liquids used with the model

Pure water, 0.3% NaCl water solution, 0.6% NaCl water solution, 0.9% NaCl water solution and human saliva are modeled in the numerical solution. The constituents of human saliva used in the numerical solution are shown in Table 4.2 (Redrow, 2009).

Table 4. 1 Composition of human saliva in the mathematical solution

Composition of human saliva	Composition [mg/mL]
NaCl	9
Protein	12.100
Lipid	10.600
Carbohydrate	9.200
DNA	0.008

Chapter 5: Results and discussion

Figure 5.1 shows the experimental result is highly fit to the numerical result. The small hump in the end of the experimental result might be due to the reflection and refraction of the light when the photos were taken. In the distilled water droplet evaporation experiment, the temperature is 23°C; the relative humidity is 50% and the wind velocity is zero.

Figure 5. 1 Water droplet evaporation: Surface area vs. Time

The results of three different concentrations of NaCl water solution droplets and human saliva droplet are illustrated in Figure 5.2. The environmental temperature is 13.5°C and relative humidity is 33%.

Figure 5. 2 0.3% NaCl water droplet evaporation: Surface area [mm²] vs. Time [s]

Some noise points in the end of the evaporation process of the three experiments were cancelled and they were caused by the salt crystallized after the water evaporated. Ideally, the salt would crystallize as a semi-sphere finally, however, when the water evaporated, the salt was left in the flat plane randomly rather than like an exact semi-sphere. From Figure 5.2, it can be observed that the numerical results and the experimental results are matched well to each other. The evaporation rates of the droplet of the salt solutions are smaller than the rate of the water droplet evaporation. Additionally, Figure 5.2 also shows the evaporation of human saliva droplet. Numerical result is good enough to predict the experimental process. The evaporation rate of the human saliva droplet is also a little bit slower than that of the pure water droplet.

Figure 5.3 shows the evaporation of different kinds of droplets at different environmental temperature and relative humidity. In Figure 5.6, “N” means numerical result; “E” means

experimental result; 0.3% means 0.3% NaCl water solution droplet, similarly to 0.6% and 0.9%; HS stands for human saliva; T is the environmental temperature. Under the environmental condition that temperature around 34.2°C and relative humidity around 26%, the droplets include 0.3% NaCl water solution droplet, 0.6% NaCl water solution droplet, 0.9% NaCl water solution droplet; under the environmental condition that temperature around 23°C and relative humidity around 30%, there are three groups of human saliva droplets evaporation. From Figure 5.2.8, it can be observed that the experimental results fit well with the numerical results. The three groups of human saliva droplets evaporation can provide us the reliability of the numerical solution.

**Figure 5. 3 Results of Evaporation of different droplets under various environmental temperatures:
Surface area [mm²] vs. Time [s]**

Figure 5.4 shows all the groups of the human saliva droplet evaporation that have performed under high environmental temperature (36.7°C) and relative humidity (25%), medium temperature (23°C) and relative humidity (30% and 38%), and low temperature (13°C, 2°C) and relative humidity (33%). In Figure 5.7, “N” means numerical result; “E” means experimental result; T is the environmental temperature.

Figure 5. 4 The evaporation results of human saliva droplets at different temperature and relative humidity; Surface area [mm²] vs. Time [s]

Figure 5.5 shows that if the environment temperature increases, the evaporation will be faster, and keeping the temperature constantly, if the relative humidity increases, the evaporation rate will be slower. It can be concluded that at different temperature and relative humidity, the evaporation changes with environmental temperature and relative humidity. The numerical results are matched well with the experimental results.

Figure 5. 5 Evaporation of human saliva droplets under different environmental temperature, similar relative humidity

Figure 5.6 illustrates the experimental results and numerical results of 0.9% NaCl water solution droplets and brewed coffee droplet evaporation.

Figure 5. 6 Evaporation of coffee and 0.9% NaCl water solution droplet: Temp=22°C, RH=33%

Table 5.1 is showing the comparison of numerical results from the Matlab program and experimental results from other authors.

Table 5. 1 Comparison of numerical results: Matlab vs. experiments

Author	Solution	Temperature [°C]		RH	Initial diameter [mm]	Evaporation Rate [mm ² /s]		
		Td	Tatm			Experiment	Numerical Result [Zhang, 2011]	Error
Smolik et al.	pure water	14.85	24	35%	1.2	-0.0064	-0.0061	4.69%
Ranz & Marshall		9.11	24.9	0	1.05	-0.003	-0.0031	3.33%
Molye et al.* (Environmental Pressure is 596hpa)		-33.5	-33.5	36%	5.00E-02	-1.29E-04	-1.24E-04	4.11%
		-33.5	-33.5	36%	4.72E-02	-1.32E-04	-1.25E-04	5.41%
		-33.5	-33.5	36%	4.46E-02	-1.33E-04	-1.24E-04	6.26%
		-33.5	-33.5	36%	4.20E-02	-1.25E-04	-1.18E-04	5.88%
		-33.5	-33.5	36%	3.70E-02	-1.36E-04	-1.26E-04	7.70%

Table 5.2 shows the experimental results of human saliva droplets evaporation performed in this study and the numerical results under the same experimental conditions.

Table 5. 2 Evaporation rate of human saliva droplet: experiment vs. numerical results

Solution	Temperature [°C]		RH	Initial diameter [mm]	Evaporation Rate [mm ² /s]		
	Td	Tatm			Experiment	Numerical Result	Error
human saliva	23	23	30%	0.81	-0.0037	-0.0035	5.41%
	23	23	30%	0.74	-0.0037	-0.0035	5.41%
	13	13	25%	0.90	-0.0031	-0.0031	0.00%
	36.7	36.7	25%	0.80	-0.0083	-0.0086	3.61%
	36.7	36.7	38%	0.68	-0.0083	-0.0086	3.61%
	2	2	82%	0.59	-3.69E-04	-3.62E-04	1.90%
	23	23	30%	0.74	-0.0037	-0.0036	2.70%
	23	23	30%	0.81	-0.0036	-0.0036	0.00%
	23	23	30%	0.81	-0.0037	-0.0036	2.70%
	0.7	0.7	35%	0.42	-0.0004	-0.0005	7.77%

Table 5.3 shows the experimental results of NaCl water solution droplets and other droplet evaporation performed in this study and the numerical results under the same experimental conditions.

Table 5. 3 Evaporation rate of other kinds droplets: experiment vs. numerical results

Solution	Temperature [°C]		RH	Initial diameter [mm]	Evaporation Rate [mm ² /s]		
	Td	Tatm			Experiment	Numerical Result	Error
0.3% NaCl water solution	13.5	13.5	33%	0.73	-0.0019	-0.0019	0.00%
	34.2	34.2	26%	0.97	-0.0079	-0.0080	1.27%
	34.2	34.2	26%	0.97	-0.0079	-0.0080	1.27%
0.6% NaCl water solution	13.5	13.5	33%	0.92	-0.0019	-0.0019	0.00%
	34.2	34.2	27%	1.04	-0.0076	-0.0075	1.32%
0.9% NaCl water solution	35	35	26%	0.97	-0.0065	-0.0067	3.08%
	13.5	13.5	33%	0.83	-0.0018	-0.0018	0.00%
	22	22	33%	1.00	-0.0030	-0.0030	0.00%
brewed coffee	22	22	33%	1.00	-0.0030	-0.0029	3.33%

In Figure 5.7, under various temperature and constant relative humidity, the evaporation rate varies. When the temperature is increasing, the evaporation rate will increase, and contrarily, the evaporation rate will decrease.

Figure 5. 7 Numerical results of human saliva droplets under different temperature, same relative humidity

On the other hand, as showing in Figure 5.8, under constant temperature and various relative humidity, the evaporation rate also varies. When the relative humidity of the ambient environment is increasing, the evaporation rate will decrease, and when it is decreasing, the evaporation rate will increase.

Numerical results: Semi-sphere human saliva Droplets evaporation (Constant Temp.), $D_0=1\text{mm}$

Figure 5. 8 Numerical results of human saliva droplets under different relative humidity, same temperature

In order to obtain a droplet with the same evaporation rate of human saliva droplet, Figure 5.9 was provided by showing the numerical results, including all kinds of droplets which have the same initial diameter (1mm) in the study at the same temperature and relative humidity. Figure 5.9 tells that when the salinity increases, the evaporation rate will decrease, that is to say the water droplet has the largest evaporation rate among these kinds of droplets, and 1.2% NaCl water droplet has the slowest evaporation rate.

Figure 5. 9 Numerical results of evaporation of different droplets

Figure 5.10 shows the evaporation process of an artificial human saliva and human saliva droplet under same environmental conditions (23°C and 38% relative humidity) and same initial diameter 1mm. In order to make an artificial human saliva, run the numerical solution code of 1mm diameter human saliva droplet at 23°C, 30% to obtain the result of time that the droplet evaporates completely, and then make the lipid and DNA concentration equal to zero, and try to run the code with the other three components concentration: salt, protein and carbohydrate to obtain the closest result with human saliva.

Figure 5. 10 Numerical solution of evaporation of artificial human saliva evaporation vs. Human saliva

In Figure 5.11, the temperature changed during the evaporation process.

Figure 5. 11 Human saliva droplet evaporation: temperature [°C] vs. time [s]

It can be observed that the temperature falls dramatically at the initial evaporation process to 10°C , and then almost remains constant. The sharp decrease in temperature at the beginning is due to the latent heat of evaporation. At the end of the evaporation process, the temperature decrease again, this is due to the change of density of the liquid (see Equation 4.17).

Chapter 6: Conclusions

The surface tension and evaporation rate of different droplets has been measured and analyzed in this study. Employing Matlab techniques and software, the surface tension and evaporation rate of different kinds of droplet have been calculated or simulated. It can be calculated that for water, if the temperature increases 20°C, the surface tension of water will decrease 4.33%.

When the salt concentration increases, the surface tension of the water solution will increase; contrarily, when the glucose concentration increases, the surface tension of the water solution will decrease.

Furthermore, salt decreases the evaporation rate of water droplet. It is reasonable that the intermolecular forces of atoms and molecules may repel or attract all elements. In the case of a soluble salt when dissolved into water it forms hydrogen bonds with the water through the dipole ends of the water molecule and the salt. These bonds make it necessary to apply more kinetic energy to create enough movement to break the bonds and the attraction between water molecules to change of state, in this case liquid to gas. If the temperature increases, the evaporation rate will be faster, and if the relative humidity increases, the evaporation rate will be slower, which can be concluded that when the temperature increases, the kinetic energy of the molecules of water will increase, and when the relative humidity increases, the concentration of water vapor in the ambient environment will increase which can restrain the water molecules evaporate

Under various temperature and constant relative humidity, the evaporation rate varies. When the temperature is increasing, the evaporation rate will increase, and contrarily, the evaporation rate will decrease. On the other hand, under constant temperature and various relative humidity, the

evaporation rate also varies. When the relative humidity of the ambient environment is increasing, the evaporation rate will decrease, and when it is decreasing, the evaporation rate will increase.

When the salinity increases, the evaporation rate will decrease, that is to say the pure water droplet has the largest evaporation rate among these kinds of droplets: 0.3% NaCl water solution droplet, 0.6% NaCl water solution droplet, 0.9% NaCl water solution, 1.2% NaCl water solution droplet, and 1.2% NaCl water solution droplet has the slowest evaporation rate.

In order to make artificial human saliva, numerical solution is used and environmental conditions are: temperature=23°C; relative humidity=38%. The components of the artificial human saliva are shown in Table 6.1. It has the same evaporation time as human saliva droplet.

Table 6. 1 The concentration of components of artificial human saliva

	Concentration [mg/mL]
Salt	9
Protein	30
Carbohydrate	35
Lipid	0
DNA	0

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Appendix I

This appendix shows the calculation of how long the tap water takes to obtain the same temperature with the environment. The initial temperature is not a factor that can influence the result. The solution is contained in a beaker and the shape of water can be considered as a cylinder, which has a volume of $1 \times 10^{-5} m^3$; the height and the diameter of the section of the cylinder are 0.08m. There is no obvious convection factor.

$$\text{Characteristic Length: } L_c = \frac{V}{A_s} = \frac{1 \times 10^{-5} m^3}{\pi \left[(0.08m)^2 \times 2 + 0.08 \times 2 \times 10^{-3} \right]} = 2.5 \times 10^{-4} m$$

$$\text{Biot number: } Bi = \frac{hL_c}{K} = \frac{15 W/m^2 K \times 2.5 \times 10^{-4}}{0.58 W/mK} = 6.45 \times 10^{-3} < 0.1$$

Lumped system analysis is valid to solve this problem:

$$b = \frac{hA_s}{\rho V c_p} = \frac{15 \times 0.041}{1000 \times 10^{-5} \times 4200} = 0.0146 s^{-1}$$

$$0.00001 = e^{-bt} = e^{-0.0146t}$$

$$t = 13.14 \text{ min}$$

Appendix II

```
//
clear all;close all;clc

fns = dir('*.jpg');
fnames = char(fns.name);
fdates = datevec(char(fns.date));
[j,k]=size(fnames);
ini_crop=[1150 1880 180 410];
vol(j)=0.4664; %Needle Volume

for i=1:j
    I=imread(fnames(i,:));
    I2=imrotate(I,90);
    I3=imcrop(I2,ini_crop);

    %BW = im2bw(I3,0.5);%graythresh(I3+10)); %to be fixed
    BW=(1-bwmorph((1-im2bw(I3,0.56)),'clean'))); % 'bwmorph, clean'removes
isolated pixels
    BW3=double(BW);
    box = regionprops(BW3, 'BoundingBox', 'centroid');
    if i == 1
        xw1 = box.BoundingBox(3);
        yw1 = box.BoundingBox(4);
    end
    ctr_x = box.Centroid(1);
    ctr_y = box.Centroid(2);
    % I4=imcrop(I3,[ctr_x-xw1/2-15 ctr_y-yw1/2+120 xw1+60 yw1-150]);
    I5=imresize(I3,1.2); %to be fixed
    imshow(I5)

    [m,n] = size(BW3);
    verlin_x(1:m) = ctr_x;
    verlin_y = 1:m;

    BWT_1=1-BW3;% inverse: turns 1-0, 0-1
    BWT_1=BWT_1(:,1:round(size(BW3,2)/2)+20); % Cut the shadow in the right
part
    % r_t=round(size(BW3,1)/2)-2:round(size(BW3,1)/2)+2; % the row of the
water center (5 length)
    % c_t=[round(size(BW3,2)/2)-20 round(size(BW3,2)/2)-20
round(size(BW3,2)/2)-20 round(size(BW3,2)/2)-20 round(size(BW3,2)/2)-20]; %
the col of the water center (approximately)
    c_t=1:size(BWT_1,2); % the column of the water center (approximately)
    r_t=round(size(BW3,1)/2)*ones(size(c_t)); % the row of the water center
(5 length)
    BWT_2=bwselect(BWT_1,c_t,r_t); % select the main body of the water
    [r_t c_t]=find(BWT_2==1); % select the coordinates of water
    r_t_max=max(r_t); % find the lowest point's row number
    i_t=find(r_t==r_t_max); % find the index of that point
```



```

    i_t=i_t(ceil(length(i_t)/2)); % in case there are more than 1 point,
select the middle one
    ctr_x=c_t(i_t); % then find the column number of that point

    SBW = BW3(:,1:round(ctr_x));
    [m,q]=size(SBW);
    n=ctr_x;
    SBW1 = edge(SBW,'canny');

    for ii = 1:m
        ind = find(SBW1(ii,:),1,'first');
        if (isempty(ind)); ind = n; end;
        zero_pix(ii) = ind;
    end

    zero_pix2 = n - zero_pix+15;
    pixlen = 0.406/81; %pixlen = 0.28702/47.13; Blue needle
    drop_y = [1:length(zero_pix2)]*pixlen;
    drop_r = zero_pix2*pixlen;
    ppx = polyfit(drop_y,drop_r,6);
    fy = @(y) pi.*(ppx(1)*y.^6+
ppx(2)*y.^5+ppx(3)*y.^4+ppx(4)*y.^3+ppx(5)*y.^2+ppx(6)*y.^1+ppx(7)*y.^0);
    miny=min(drop_y);
    maxy=max(drop_y);
    sur(i)= quad(fy,miny,maxy);%just droplet without nylon thread

    et(i)=etime(fdates(i,:),fdates(1,:));
    timtxt = num2str(et(i));
    ttlstr = strcat('Time: ',timtxt,' s');
    text(10,20,ttlstr,'FontSize',12,'Color','k');

    surtxt = num2str(sur(i),'%1.2f');
    ttlsur = strcat('Surface Area: ',surtxt,' mm^2');
    text(10,40,ttlsur,'FontSize',12,'Color','k');

    if i==1;
        evap_rate(1)=0;
    else
        evap_rate(i)=(sur(i)-sur(i-1))/(et(i)-et(i-1));
    end;
    evaptxt = num2str(evap_rate(i),'%1.4f');
    ttlevap=strcat('Evap.rate: ',evaptxt,' mm^2/s');
    text(10,65,ttlevap,'FontSize',12,'Color','k');

    F(i) = getframe;
end
movie2avi(F,'example.avi','compression','None','quality',100,'fps',2);

for i=2:j
    lambda_e(i-1) = (sur(i)-sur(i-1))*1e-6/(et(i)-et(i-1))/pi
    lambda_e_mean = mean(lambda_e)
end

% evaporation of a pure water droplet

```

```

Dv = 2.4*10^-5;% water diffusivity m2/sec
M = 18.02;% molecular weight of water
R = 8.314;%universal gas constant
den=998.2;%water density kg/m3
RH=0.33; % Relative humidity of the environment
Pd=2.744;% droplet pressure
Pi=RH*Pd;%pressure of the environment
T=273.15+23; % Temperature 22 celsius

%vol_0=vol(1)*1E-9;% in m^3
%d_0=(6*vol_0/pi)^(1/3);% in meters
lamda=4*Dv*M*(Pd-Pi)/(R*den*T);%evaporation constant
%t_evap=d_0^2/lamda;%lifetime or evaporation time
sur_0 = sur(1)*1e-6;
t_evap=sur_0/lamda/pi;

%n = length(sur);
t = 0:t_evap;
sur_t = sur_0 - pi*lamda*t;
d_0 = (sur_0/pi)^0.5;

figure(1)
title('Semi-sphere Droplet evaporation');
%plot(et/t_evap,(sur-sur(54))/(sur(1)-sur(54)),'^b',t/t_evap,sur_t/sur_0,'r')
% plot(et/t_evap,(sur-sur(29))/(sur(1)-sur(29)),'^b',t/t_evap,sur_t/sur_0,'r')
plot(et/t_evap,((sur-0.01)/(sur(1)-0.01)),'^b',t/t_evap,sur_t/sur_0,'r')
legend('Experiment of Distilled Water','Numerical Solution for pure water');
xlabel('Time / Analytical Pure Water Evaporation Time')
ylabel('Droplet Surface Area / Initial Droplet Surface Area')
grid on
ylim([0 1])

figure(2)
plot(et,sur,'^b',t,sur_t/(1e-6),'r')
legend('Experiment of Distilled Water','Numerical Solution for pure water');
xlabel('Time[s]')
ylabel('Surface Area [mm^2]')
//

```

Appendix III

```
//

clear all
clc

T_d=273.15+23; % droplet temperature [K]
T_inf=T_d; % Ambient Temperature [K]
% T = 273.15+50;
T_0 = 273.15; %reference temperature
TC = T_inf-T_0; % Ambient Temperature [C]
T_dC=T_inf-T_0;

P=1013.25; %reference pressure [hpa]
P_a=1013.25;

R=8.314472; %J/K mol
RH = 0.38;

d = (1)*1e-3; %m
r=d/2;
vol=(1*pi*r^3)/6;
vol_semi = vol;

%Calculate Sherwood Number
V=0; %wind velocity
den_air = 1.1839; % [m3/kg] @25C
rho_a = den_air;
miu_air = 18.3*1e-6; %[kg/m.s]@25C

%Constituents in droplet kg/m^3
salt=9.00; % If this is the water, it should be 0,
pro=19.9;
lip=18.1;
carb=12.3;
dna=0.820;

% salt=9.00; % If this is the water, it should be 0,
% pro=30;
% lip=0;
% carb=35;
% dna=0;
% salt=0.001; % If this is the water, it should be 0,
% pro=0;
% lip=0;
% carb=0;
% dna=0;

m_pro=pro*vol;
m_lip=lip*vol;
m_carb=carb*vol;
```

```

m_dna=dna*vol;
m_salt=salt*vol;

% Density of water
rho_w=999.842594 + 6.793952e-2*TC - 9.095290e-3*TC^2 + ...
    1.001685e-4*TC^3 - 1.120083e-6*TC^4 + 6.536332e-9*TC^5;
m_w = rho_w * vol;

% droplet total mass
m_tot=m_pro+m_lip+m_carb+m_dna+m_salt+m_w;

% mass fractions
x_pro=m_pro/m_tot;
x_lip=m_lip/m_tot;
x_carb=m_carb/m_tot;
x_dna=m_dna/m_tot;
x_salt=m_salt/m_tot;
x_water=m_w/m_tot;

%densities of each component [kg/m3]
rho_salt=2160;
rho_pro=1362;
rho_lip=1100;
rho_carb=1562;
rho_dna=1650;

%Molecular weight of each component
M_w=18.02;
M_s=58.4;
M_a=29;
M_pro=66500;
M_lip=255;
M_carb=180.16;
M_dna=700;

D_v_original=2.11e-5*(T_d/T_0)^1.94*(P/P_a);
D_v=D_v_original/((r/(r+(5e-
8)))+(D_v_original/(r*0.0020))*((2*pi*M_w)/(1000*R*T_d))^0.5));
%D_v = 2.04e-5;

% specific heat of dry air, const press, T_inf = -40 to 40 C for press near
latm
c_p_d=1005.60 + 0.017211*T_dC + 0.000392*T_dC^2;

% thermal conductivity of air (W/mC)
k_a_0=2.411e-2*(1 + 3.309e-3*T_dC - 1.441e-6*T_dC^2);

% sherwood number
Sh = 2+0.6*(miu_air/den_air/D_v)^(1/3)*(d*V*den_air/miu_air)^0.5;

% saturation vapor pressure
e_sat=6.1121*(1.0007+(3.46e-6)*P)*exp((17.502*T_dC)/(240.97+T_dC));

% total density of droplet
rho_s=(x_pro/rho_pro+x_lip/rho_lip+x_salt/rho_salt+x_dna/rho_dna+...

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x_carb/rho_carb+x_water/rho_w)^(-1);

% mass of water in the droplet
m_w=rho_w*(vol-(m_salt/rho_salt+m_pro/rho_pro+m_lip/rho_lip+...
    m_dna/rho_dna+m_carb/rho_carb));
delta=T_d/T_inf-1;

% volume of solid part
vol_sol=((m_salt/rho_salt + m_pro/rho_pro + m_lip/rho_lip + ...
    m_dna/rho_dna + m_carb/rho_carb));

% the radius of the solid part
r_sol=(6*vol_sol/pi)^(1/3);

%% Latent heat
L_v=(25.00-0.02274*TC)*10^5;

% Surface tension of water
sig_w=0.2358*((374.00-TC)/647.15)^1.256*(1-0.625*((374.00-TC)/647.15));
% Surface tension
sig_s=sig_w*0.01;

% the number of ions into which a salt molecule dissociates
nu_ion = 2;

mf_salt = m_salt/m_w;
mf_carb = m_carb/m_w;%m_carb/(m_tot-m_w);
mf_pro  = m_pro /m_w;%m_pro/(m_tot-m_w);

rho_sol=(m_pro+m_lip+m_carb+m_dna+m_salt)/vol_sol;

%% molalities (of binary solution)
molal_s=(m_salt/M_s)*1000/m_w;
molal_c=(m_carb/M_carb)*1000/m_w;
molal_p=(m_pro/M_pro)*1000/m_w;

% practical osmotic coefficients
phi_s=0.0055*molal_s^2+0.028*molal_s+0.9128;
% high concentration limiting condition
if phi_s > 1.5
    phi_s=1.5;
end
phi_c=0.0233*molal_c+1;
% high concentration limiting condition
if phi_c > 1.2
    phi_c=1.2;
end
phi_p=22.0357*2099560^molal_p-21.718;
% efflorescence conditions (for BSA protein)
if RH<0.50

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    dRH=((RH)^0.5-0.5916);
    phi_p=55*((0.70711-0.5916)-dRH)/(0.70711-0.5916))+ ...
        phi_p*dRH/(0.70711-0.5916);
    if dRH<0
        phi_p=55;
    end
end

%% Solve for the equation
x_start = r;
x_end = r_sol; %m

x(1) = x_start;
t(1) = 0;

N_x = 151;
delta_x = (x_end - x_start)/(N_x-1);

for i=2:N_x
    x(i) = x(i-1) + delta_x;
end
sum = 0.0;

t_num(1) = 0;

for i = 2:N_x

    k_a(i)=k_a_0/((x(i)/(x(i)+(2.16e-7)))+(k_a_0/(x(i)*0.7*rho_a*c_p_d))*...
        sqrt((2*pi*M_a)/(1000*R*T_d)));
    k_a(1)=k_a(2);

    sum_num(i) = 2/(((Sh*D_v*M_w*e_sat)/(2*rho_s*R*T_inf*10*x(i)))*(RH-
(1/(1+delta))* ...
    exp(((L_v*M_w)/(R*T_inf*1000))*(delta/(1+delta))+ ...
    ((2*M_w*sig_s)/(R*T_inf*(1+delta)*rho_w*x(i)*1000))-...
    ((M_w*rho_sol*r_sol^3)/(rho_w*(r^3-r_sol^3)))*...
    (nu_ion*phi_s*mf_salt/M_s + 1.01*phi_c*mf_carb/M_carb+...
    phi_p*mf_pro/M_pro))))*delta_x;

    t_num(i) = t_num(i-1)+ sum_num(i);

    vol_num(i)=(1*pi*x(i)^3)/6;
    D_squared(i) = (2*x(i))^2;
    sur_num(i)=D_squared(i)*pi;
    sum_num(1)=sum_num(2);

%     vol_solid = 1/6*pi*(x(5001))^3;
    vol_solid = 1/6*pi*(x(101))^3;

    vol_water(i) = vol_num(i)-vol_solid;
    m_water(i) = rho_w*(vol_water(i));
    m_water(1)=m_water(2);
    %m_water(5001)=0;
    m_water(101)=0;

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```

    rho_drop(i)
    =(m_pro+m_lip+m_carb+m_dna+m_salt+m_water(i))/((1*pi*x(i)^3)/6);
    rho_drop(1) = rho_drop(2);
    deta(i) = L_v*rho_drop(i)/k_a(i)*x(i-1).*delta_x/sum_num(i);

    T_d_num(i-1) = T_inf+ deta(i-1);

    delta_prime(i-1) = L_v * rho_drop(i) / T_inf/k_a(1) *
x(i)*delta_x/sum_num(i);
    %delta_prime(1) = delta_prime(2);

    T_drop(i)= T_inf * (1+delta_prime(i-1));
    T_drop(1)= T_inf;

end
    delta_prime(101) = delta_prime(100);
    T_d_num(101)=T_d_num(100);

t=t_num(101)

vol_num(1)=vol;
D_squared(1)=d^2;
sur_num(1)=D_squared(1)*pi;
T_d_num(1) = T_inf;

figure(1)
plot(t_num,T_d_num-273.15, 'r-.')
title('Droplet Temperature[^oC] vs. Time [s]')
ylabel('Droplet Temperature[^oC]')
xlabel('Time [s]')
//

```