Heat and Mass Transfer in 2-Propanol Droplet Evaporation: Analysis Modified Stagnant Film Model

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Abstract. Heat and mass transfer is an evaporation process from liquid droplet that occur in spray drying technology. So, it becomes important to understand the basic elements of spray drying, namely droplet. The formation technology involves drying is used in many industries. Various models of analogies of heat and mass transfer analogies have been formulated, with the aim of obtaining the characteristics that occur in the system. The analogy model most often used to obtain heat and mass transfer coefficients from droplet is the analogy model Ranz W. E. and Marshall W. R. The analogy has requirements, including the Lewis number (Le) which ranges in the number one. The purpose of this experiment is to compare the results obtained from the analogy of the Ranz-Marshall equation model applied to the droplet by making a modification of the C1 and C2 values that exist in the stagnant film model. In this experiment, the analysis results obtained from the modification of the stagnant film model is that the heat transfer phenomenon that occurs in droplet does not yet fully have good results. Where the value of C1 still cannot represent the value that can be used to obtain C2 properly.

1. Introduction

In recent years, the rapid growth of attention to theoretical and experimental studies of the behavior a single droplet evaporation is increasing [1]. One process that has been used from the past until now we still use to support our daily needs is the evaporation process. The process of evaporation in liquid fuels is still the world's main energy source because the density of its energy is fairly high, and also its handling is fairly easy. When liquid fuel is used, spray combustion is also commonly used. This spray combustion is used in many industries such as turbine engines and diesel engines [2]. Thus, it is important to understand the characteristics that occur in spray combustion [3]. Testing on droplets is one of the steps used for these needs. The dynamic nature possessed by droplets, as well as the heat transfer from droplets to hot surfaces, is one of the important factors that will affect the mass transfer from droplets [4].

In order to increase the effectiveness and efficiency of the spray combustion, a study is needed to determine the characteristics that exist [5]. Various models of the analogy to heat and mass transfer analogy have been formulated to show the characteristics that occur in the system. The analogy model of heat and mass transfer which is generally used is the analogy model of Ranz W. E. and Marshall W. R. [6, 7], through which we can obtain the value of the heat transfer and mass droplet. The analogy will have a valid value if it has a value of the Lewis number equal to one. This value will guarantee the similarity of the temperature profile and the concentration profile of the tested liquid [8]. In addition to
the Ranz-Marshall analogy, there are 3 other models used, namely the Stagnant film model, the penetration model, and the laminar boundary model [9].

Based on the results of research conducted by E.A. Kosasih and M.I. Alhamid by making a modification to the stagnant film model, good compatibility is obtained. The results are obtained from water fluids, where the Lewis number owned by water is less than one [8]. But the results obtained are inversely proportional to E.A. Kosasih and D. Prasetyo [7] and also E.A. Kosasih and I. Agung [6], where the value of their Lewis number has a value of more than one and obtains a less good correlation. Experimental investigation has been conducted to study the effect [10]. The purpose of this experiment is to obtain a modification of the stagnant film model that will be used to obtain a good correlation with more than one Lewis value. In this experiment, the modification is located on the values of C1 and C2 used. The value of C1 represents the integral of mass transfer and the value of C2 represents the value of heat transfer.

2. Literature Review
In conducting experiments, various kinds of literature are used that will underlie these experiments. The literature will also be used to obtain the origin of the modified formula.

2.1. Volume of Sphere
To get the volume sphere from what was previously in the form of prolate spheroid, the following formulas are used:

2.1.1. Prolate Spheroid. A prolate spheroid is a spheroid that has a polar radius greater than its equatorial radius. The formula used in prolate spheroid is written as follows [11]:

\[ V_{\text{prolate}} = \frac{4\pi}{3} a^2 c \]  
(2.1)

\[ A_{\text{prolate}} = 2\pi a^2 + 2\pi \frac{ac}{e} \sin^{-1} e \]  
(2.2)

\[ e_{\text{prolate}} = \sqrt{1 - \frac{a^2}{c^2}} \]  
(2.3)

2.1.2. Spheroid. A spheroid is an ellipsoid that has the same length of radius on both axes. The formula of the spheroid is written as follows [11]:

\[ d_{\text{sphere}} = \frac{6V}{A} \]  
(2.4)

\[ V_{\text{sphere}} = \frac{\pi d^3}{6} \]  
(2.5)

\[ A_{\text{sphere}} = 4\pi r^3 \]  
(2.6)

2.2. Ranz-Marshall Analogy
Based on the formula obtained from Ranz, W. E., & Marshall, W. R. [12], two equations are used as follows, where:

- Equation for heat transfer:

\[ Nu = 2 + 0,6Re^{1/2} Pr^{1/3} \]  
(2.7)

- Equation for mass transfer:

\[ Sh = 2 + 0,6Re^{1/2} Sc^{1/3} \]  
(2.8)
2.3. Stagnant Film Model
The stagnant film model can be illustrated with figure 1. That picture shows an evaporation of a cold liquid surrounded by a hot environment that carries the heat temperature of the heater to the liquid.

![Figure 1. Illustration of stagnant film model](image)

The total mass transfer rate of material A defined as \( N_{A0} \), where \( \delta_c \) is the thickness of concentration film, \( C \) is total concentration of A and B, \( D_{AB} \) is mass diffusivity, \( X \) is mole fraction, and where \( k_c \) is the mass transfer coefficient [8].

\[
\exp\left(\frac{N_{A0}\delta_c}{C_{D_{AB}}}\right) = 1 + \frac{X_{A0} - X_{A\infty}}{1 - X_{A0}}
\]  (2.9)

\[
N_{A0} = k_c \left( X_{A0} - X_{A\infty} \right) / \left( 1 - X_{A0} \right)
\]  (2.10)

Because of \( X_\delta = X_\infty \), eq. (2.9) and eq. (2.10) become,

\[
\exp\left(\frac{N_{A0}\delta_c}{C_{D_{AB}}}\right) = 1 + \frac{N_{A0}}{k_c}
\]  (2.11)

When \( N_{A0} \) is approaching 0 on \( k_c \), so \( k_c \) for low mass transfer approach to \( k_{CL} \). we will obtain,

\[
k_{CL} = \lim_{N_{A0} \to 0} k = \lim_{N_{A0} \to 0} \frac{N_{A0}}{\exp\left(\frac{N_{A0}\delta_c}{C_{D_{AB}}}\right) - 1}
\]  (2.12)

From eq. (2.9), can be simplified into,

\[
N_{A0} = k_{CL} \left[ \ln \left( \frac{1 - X_{A\infty}}{1 - X_{AB}} \right) - C1 \right]
\]  (2.13)

Total heat transfer is defined as below where \( T \) is the temperature, \( k \) thermal conductivity, \( \overline{C_{pa}} \) the molal specific heat.

\[
q_0 = \frac{N_{A0} \overline{C_{pa}}(T_\infty - T_0)}{\exp(-N_{A0}\overline{C_{pa}}\delta_T/k) - 1}
\]  (2.14)
Using heat transfer coefficient, $h$, total heat transfer can be also defined as,

$$q_0 = h(T_0 - T_\infty)$$  \hspace{1cm} (2.15)

From equation (2.14) and eq. (2.15) can be simplified into,

$$\exp\left(-\frac{N_{Ao}C_P\delta_T}{k}\right) = 1 - \frac{N_{Ao}C_P}{h}$$  \hspace{1cm} (2.16)

When $N_{Ao}$ is approaching 0 on $h$, so $h$ for low mass transfer approach to $h_L$, we will obtain,

$$h_L = \lim_{N_{Ao} \to 0} h = \lim_{N_{Ao} \to 0} \frac{N_{Ao}C_P}{h} - \exp\left(-\frac{N_{Ao}C_P\delta_T}{k}\right) + 1$$  \hspace{1cm} (2.17)

From eq. (2.14), can be simplified into

$$q_0 + q_{cond} = \frac{N_0C_P(T_\infty - T_0)}{\exp\left(-\frac{N_0C_P\delta_T}{h_L}\right) - 1}$$  \hspace{1cm} (2.18)

Since we have the value of $N_0$ and $q_0$, variation of droplet radius and temperature can be expressed as,

$$N_0 = -\left(\frac{\rho}{M}\right)\frac{dT}{dt}$$  \hspace{1cm} (2.19)

$$\frac{dT}{dt} = 3 \left(\frac{q_0 - N_0h_f_g}{N_0C_P}\right)$$  \hspace{1cm} (2.20)

By using all the formulas above, $C_1$ and $C_2$ then will be varied to overlook the best value of the constant for the modified stagnant film model

3. **Methodology**

In this experiment, the equipment that will be used in the experiment is arranged as shown in figure 2. The test was conducted in heat transfer laboratory, 6th floor MRC building, faculty of engineering, Universitas Indonesia. The main equipment used in this test consists of:

1. Inverter, used to adjust the speed that will be blown by the blower by changing the input frequency of electricity.
2. Shimaden SR 94, used to control the heat that will flow into the heater so that the heat that will be given as input can be controlled.
3. National Instrument (NI), used to calculate the actual data from the temperature at which the droplets are collected.

![Figure 2. Experimental setup](image-url)
In conducting data retrieval, several variations of input are needed that will be needed to obtain information from the tests to be performed. The following is input information used in this experiment is shown in table 1 below,

**Table 1. Input parameter**

| Liquid       | Temperature | Speed |
|--------------|-------------|-------|
| 2-Propanol   | 35°C        | 1 m/s |
|              | 35°C        | 7 m/s |
|              | 55°C        | 1 m/s |
|              | 55°C        | 7 m/s |

After taking data using the input parameters as in table 1, then taking pictures per frame is obtained to get diameter information from the tested droplet. The pictures taken in this experiment were taken using a digital camera as shown in figure 3 below. Data from the diameter will then be processed to obtain correlations from this experiment.

![Figure 3. Droplet picture](image)

After obtaining data from these diameters, data processing is then performed by calculating the values of C1 and C2 determined as follows in table 2:

**Table 2. The value of C1 and C2**

|        | 35°C 1 m/s | 35°C 7 m/s | 55°C 1 m/s | 55°C 7 m/s |
|--------|------------|------------|------------|------------|
| C1     | -0.025     | -0.025     | -0.025     | -0.025     |
| C1*    | -0.035     | -0.013     | -0.032     | -0.02      |
| SF     | 0          | 0          | 0          | 0          |
| C2     | -5E-08     | -5E-08     | -7E-08     | -7E-08     |
| C2*    | -5E-08     | -5E-08     | -8E-08     | -8E-08     |
| SF     | 0          | 0          | 0          | 0          |

4. Results and Discussions

After completing the research, the results obtained are the diameter and temperature of the droplet. With these results, it was calculated using the Ranz-Marshall formula as the basis for calculating the Nusselt and Sherwood number in this experiment. The value of the calculation results will certainly be used to obtain the coefficient values of h and k latent evaporation. With this value, then we will get the value of $N_{A0}$ and also the value of $q_0$. Which will then be used as a basis for determining variations with the modification of the values of C1 and C2. The value of C1 and also C1* has the result of a predetermined modification by having a value not equal to zero. Then for the value of C1 on the Stagnant Film Model has a value of 0 because of the stagnant film. Then for the C2 value determined at -5E-08; -8E-08; and -7E-08. And the C2 value on the Stagnant Film Model has a value of 0.
And based on these data, the results will be obtained as in Figure 4 and Figure 5 below. The graph shown below is a graph of the time to temperature and also radius² of the 2-propanol liquid which is being tested.

**Figure 4.** Graph temperature vs time of 2-Propanol for (a) 35°C 1 m/s, (b) 35°C 7 m/s, (c) 55°C 1 m/s, and (d) 55°C 7 m/s.

**Figure 5.** Graph radius² vs time of 2-Propanol for (a) 35°C 1 m/s, (b) 35°C 7 m/s, (c) 55°C 1 m/s, and (d) 55°C 7 m/s.

Based on the graph shown in figure 4, the graph represents the value of temperature over time that tends to increase. The characteristic findings obtained from all the variations tested have a feature that increases with time. But on the graph shown in figure 5, the results obtained are against the opposite.
Can be seen from that graphs in figure 5, where in this study the results obtained from the radius $r^2$ has decreased over time.

This phenomenon can occur because the heat exhaled by the blower is increasing. So, with this increase, the value of Reynolds number will also increase. This will make the heat transferred from the heater to droplet surface also increases. With the increase in the speed of hot air that is exhaled to the droplets, there will be an increase in latent heat and sensible heat. Sensible heat will increase due to an increase in temperature variations. And with the increasing temperature, latent heat will also increase which affects the phase change that will be faster.

Based on the results obtained in figure 4 and figure 5, can be seen that the deviation is possessed on the whole graph. In figure 4, the modified C1 value in the calculation results in an unsatisfactory temperature graph against time. These results are indicated by the results of the deviation on the graph which deviates greatly. However, the results in figure 5 show different results, where the resulting graph shows a satisfactory correlation with the results of the deviation on the radius $r^2$ graph against time which is not far apart.

Based on this research, it was found that the value of the coefficient of the stagnant film has a value that is not equal to zero. That is because the formula of the following film stagnant:

$$\exp\left(\frac{N_{A0}^C}{C \cdot D_{AB}}\right) = 1 + \frac{X_{A0} - X_{A00}}{1 - X_{A0}}$$

Based on the formula used from the stagnant film model, the values that exist in the stagnant film model will not have a value equal to zero. That is because the value of C1 will represent the droplet mass transfer integral, and the value of C2 will represent the droplet heat transfer integral. The value at C1 will intersect with the value of $r^2$ so that the stagnant film model will not have a value equal to zero.

5. Conclusion

From this experiment, concluded that modifying the value of C1 in the stagnant film model would give an unfavorable result in temperature changes graph against time. But the results obtained will be opposite with the results of the radius $r^2$ graph against time. Modifications to the stagnant film model do not yet have a good C1 value, so the value at C2 also does not get optimal results. Then we need more in-depth research to obtain equations that will produce good correlations.

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