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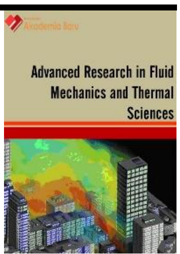

A Study on 2-Butanol Droplet: Analysis of Introduced Constant in The New Approach on Film Stagnant Model

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ABSTRACT

In many different applications, non-stationary liquid droplet evaporation phenomenon works as a fundamental. An accurate prediction of heat and mass transfer on non-static droplet is required for design. Ranz-Marshall analogy combined with the Stagnant film Model is utilized method of predicting single non-stationary high mass transfer rate droplet evaporation, but there are several problems regarding to the method such as Lewis number more than one, static film width, and not simultaneously calculates heat and mass transfer. In this paper, A new approach to Stagnant Film Model and its new introduced constant is briefly discussed. The value of C1 and C2 is investigated by comparing 2-butanol evaporation numerical simulation with experimental data. The New Approach deviated less when predicting radius while both still failed to predict changes in temperature. The appropriate value of C1 on predicting the right radius varied between -0.010 to -0.035 while the value of C2 is -4 x 10-8. For different set-up variables, the value of C1 differs. Therefore, the value of C1 supposed be a function that can be furtherly investigated with the following research on other substances.

Keywords:
Droplet; non-stationary; heat and mass transfer model; 2-butanol; a new approach to Stagnant Film Model

1. Introduction

The study of droplet heat and mass transfer is beneficial to the development of technology as it is widely used in many varieties of applications. One of the most widely researched branches of a droplet is the evaporation of fuel in many liquids fueled propulsion system [1, 2]. Not only fuel, scholars also implicated droplet study on cooling devices such as evaporative cooling for microprocessors [3] and cooling tower [4]. Droplet evaporation was also discussed in sprays for many applications outside of fuel such as vacuum spray cooling [5] and spray drying for food powder [6]. Droplet science also plays a huge part of daily life technology, for instance, inkjet printing technology [7], surface coating [8], oil lubrication [9], and even medical means such as blood evaporation rate [10].

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An accurate method of predicting droplet evaporation is required for design purposes. Droplet evaporation phenomenon is caused by heat and mass transfer. Heat and mass transfer coefficient used both for design and simulation is frequently calculated by using Ranz-Marshall equation [11]. This analogy required the Lewis number of one, which guarantees the similarity of temperature profiles and concentration profiles [12]. On the other hand, the Lewis number on a various droplet of substances isn't one which makes the analogy model becomes less appropriate to use [13, 14]. Besides, there are six conditions for the analogy which one of them is the low mass transfer rate, therefore the analogy is combined with other analytical model for heat and mass transfer [12].

Ranz-Marshall equation is used in three analytical models for high rate of mass transfer, which are stagnant film model, penetration model and laminar boundary model [12]. The evaporation rate calculated using these three models are almost similar. Stagnant film model is the most utilized model. The model assumes the film stagnant thickness as constant and does not depend on the mass transfer rate. Kosasih [12] performed a study regarding this matter and created a new approach to stagnant film model by assuming the film stagnant thickness changes over time. As a result, new constants were developed and for unknown yet reason the value of those constants differs for each substance [16]. The value of new constant introduced in Kosasih's [15] new approach to stagnant film model (Figure 1) on 2-butanol will be discussed thoroughly in this paper.

2. Methodology

2.1 Mathematical Formulation

As the air flows through the droplet, heat and mass transfer phenomenon occur. Reynold Number (Re) defines the characteristic of the flow which can be expressed as

$$Re = \frac{\rho v \mathrm{d}}{\mu} \tag{1}$$

where ρ, v, d, and μ are density, speed, contact diameter, and viscosity respectively. Ranz-Marshall analogy applies for heat and mass transfer carried by the flow. For heat transfer, Nusselt Number (Nu) is determined by

$$Nu = 2 + 0.6Re^{1/2}Pr^{1/3} \tag{2}$$

$$Pr = \frac{\mathrm{\mu}Cp}{\mathrm{K}} \tag{3}$$

where Pr, Cp, K are Prandtl Number, specific heat capacity, and thermal conductivity respectively. For mass transfer, Sherwood Number (Sh) is determined by

$$Sh = 2 + 0.6Re^{1/2}Sc^{1/3} \tag{4}$$

$$Sc = \frac{\mu\rho}{d} \tag{5}$$

The analogy are valid for Reynold numbers below 200. The coefficient rate of heat and mass transfer is next determined by calculating k_L (mass transfer coefficient) and H_L (heat transfer coefficient) which can be expressed as

$$k_{cL} = \frac{NuK}{d} \quad (6)$$

$$h_L = \frac{ShX_{AB}}{d} \quad (7)$$

where X is mole fraction. Stagnant film is an imaginary film without potential gradient outside of the film. The total mass transfer rate of material A, N_{A0}, is defined as

$$exp\left(\frac{N_{A0}\delta_c}{C.D_{AB}}\right) = 1 + \frac{X_{A_0} - X_{A\infty}}{1 - X_{A_0}} \quad (8)$$

where δ_c as thickness of concentration film, C as total concentration of A and B, and D_{AB} as mass diffusivity.

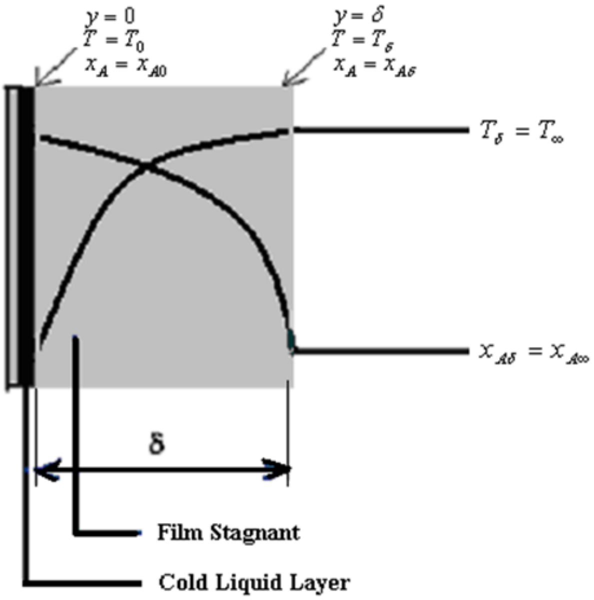

Fig. 1. Illustration of Film Stagnant Model [15]

N_{A0} can also be defined as

$$N_{A0} = k_c(X_{A_0} - X_{A\infty})/(1 - X_{A_0}) \quad (9)$$

Outside the stagnant film model applies $X_\delta = X_\infty$, therefore Eq. (8) can be expressed as

$$exp\left(\frac{N_{A0}\delta_c}{C.D_{AB}}\right) = 1 + \frac{N_{A0}}{k_c} \quad (10)$$

and when N_{A0} approaching 0 on k_c, k_c approach k_{cL} (k_c for low mass transfer) and can be defined as

$$k_{cL} = \lim_{N_{A0}\to 0} k = \lim_{N_{A0}\to 0} \frac{N_{A0}}{exp\left(\frac{N_{A0}\delta_c}{C.D_{AB}}\right) - 1} \quad (11)$$

and thus, without setting the thickness of concentration film (δ_c) as constant, the limit of Eq. (9) can be solved and integrated which resulted as

$$N_{A0} = k_{cL}\left[ln\left(\frac{1-X_{A\infty}}{1-X_{AB}}\right) - C1\right] \tag{12}$$

The value of $C1$ in the original stagnant film model is zero as a result of constant δ_c. Inside the film, the total heat transfer can be defined as q_0.

$$q_0 = \frac{N_{A0}\overline{C}_{pA}(T_\delta - T_0)}{exp(-N_{A0}\overline{C}_{pA}\delta_T/k)-1} \tag{13}$$

$$q_0 = h(T_0 - T_\infty) \tag{14}$$

with T as temperature. Since outside of the stagnant film doesn't applied potential gradient, Eq. (11) and (12) can also be defined as

$$exp\left(-\frac{N_{A0}\overline{C}_{pA}\delta_T}{k}\right) = 1 - \frac{N_{A0}\overline{C}_{pA}}{h} \tag{15}$$

when N_{A0} approaching *0* on *h*, h approach *hl* (*h* for low mass transfer) and can be defined as

$$h_L = \lim_{N_{A0}\to 0} h = \lim_{N_{A0}\to 0} \frac{N_{A0}\overline{C}_{pA}}{-exp\left(-\frac{N_{A0}\overline{C}_{pA}\delta_T}{k}\right)+1} \tag{16}$$

and thus, without thickness of concentration film (δ_c) as constant, the limit of Eq. (14) can be solved and integrated which resulted as

$$q_0 + q_{cond} = \frac{N_0 C_P(T_\infty - T_0)}{\exp\left(-\frac{N_0 C_P}{h_L} - \frac{C_2 C_P}{k_L}\right)-1} \tag{17}$$

where q_{cond} as heat conducted by the thermocouple which is equal to zero in natural phenomenon. Since we have the value of N_0 and q_0, variation of droplet radius and temperature can be expressed as

$$N_0 = -\left(\frac{\rho}{M}\right)\frac{dr}{dt} \tag{18}$$

$$\frac{dT}{dt} = 3\left(\frac{q_0 - N_0 h_{fg}}{N_0 r C p_A}\right) \tag{19}$$

where M as Mole of droplet and h_{fg} as saturated pressure. When coupled with initial conditions t=0, T=T_0, r=r_0, Eq. (18) and (20) constitute the inital value problems for ordinary differential equation. Therefore, it can be used for a numerical simulation.

2.2 Experiment Apparatus

Experiment data were also obtained to validate the compatibility between the new apporach to stagnant film model and the constants. An experiment was done by adjusting the temperature and flow speed of air through the droplet. Blower CZR-900 were used coupled with Inverter Hossoni HB-V9-R76T2 to set the blower's RPM by manipulating inverter frequency (Figure 2). Hot wire anemometer was used to read the airflow speed. For temperature, a 3kW 220 VAC heater was coupled with digital counter to manipulate the air temperature. After the air temperature and velocity had been steady, 2-butanol were coiled into thermocouple forming a droplet.

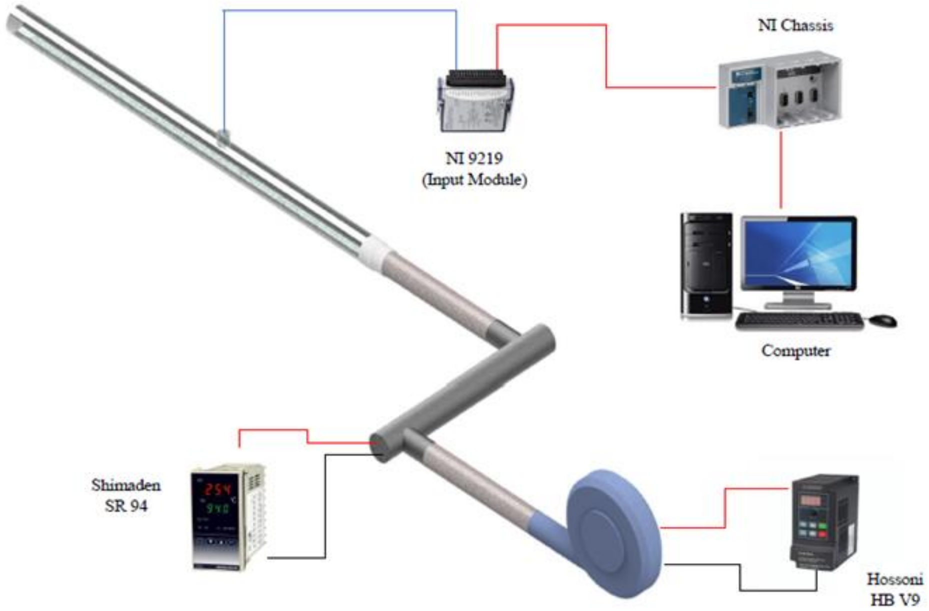

Fig. 2. Data retrieval scheme

Type K thermocouple was connected to the NI - DAQ that sends temperature records to the Labview computer program. Change in radius was recorded by taking video with DSLR camera which is enchanted with macro lenses. Video of droplet change in radius, then croped into 60 images per second with imageJ, which then can be used to find the radius by calculating the pixels.

2-Butanol radius and temperature data were recorded every 5 seconds through total four different combinations of circumstances of varying air flow speed and air temperature shows in Table 1. To note with, the droplet starting temperature is affected by the starting temperature value which caused the surrounding temperature to change which is stated in Table 2.

Table 1
Temperature and speed variation on airflow

Temperature Variation	Speed Variation
35°C	1 m/s
55°C	7 m/s

Table 2
Droplet initial condition for each trial variation

Temperature Variation	1 m/s	7 m/s
35°C	25.51°C – 1.25 mm	35.47°C – 1.18 mm
55°C	27.21°C – 1.01 mm	34.61°C 1.06 mm

3. Results

ODE provided in the mathematical formulation is executed into numerical simulation. The initial value of temperature and radius were set as the same as the experiment for each variables which is showed by Table 2.

The value of C1 and C2 is unknown, therefore we first range the value of C2. C1 and C2 affect each other indirectly. The range value of C2 lies between -4 x 10^{-8} to -8 x 10^{-8} and having the constant out of that range resulting in numerical error on any value of C1. The value -4 x 10^{-8} is done in the simulation since the deviation to experiment less than the other values. For C1, multiple value were set for model trial according to its compatibility to the experiment result.

Both simulation and experiment were then executed and ploted into Figure 3 to Figure 10. Figure 3 to Figure 6 shows the change of square radius by time while Figure 6 to 10 shows the change of temperature by time. Four series of plot can be found on the graphs. Black square, blue triangle, red dot, and green triangle respectively represent experiment data, modified stagnant film model with the most apropriate C1 value (C1*), modified Stagnant film model with average C1 value of those 4 most apropriate value (C1), and the Standard Stagnant Film Model (SFM).

Figure 3 to Figure 6 shows the reduction in radius square value by time. Both model predicted the reduction, however the deviation in reduction data differs. Predicted value of radius square by using the original stagnant film model deviates unconsistently from the experiment. In the other hand, with the new approach to stagnant film model the predicted radius square deviates less from the experiment for the right value of C1 (C1*). The value of average apropriate C1 (C1) also deviates unconsistently. Since the value of C1 is different for different parameters, therefore the value of C1 should be considered as a function. Hereby, the value of C1 with a constant C2 that is used in the numerical simulation is provided by Table 3.

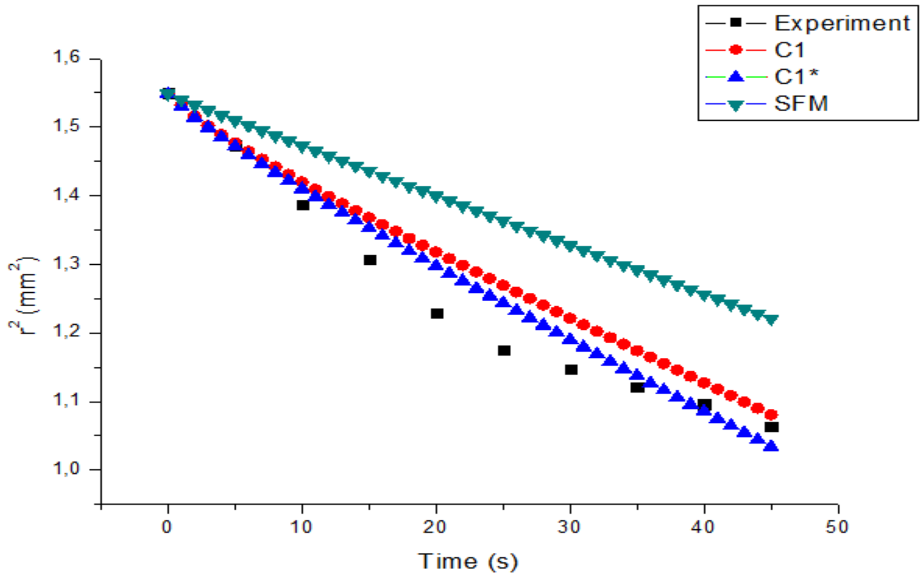

Fig. 3. 2-butanol change in radius square by time (35°C 1 m/s airflow)

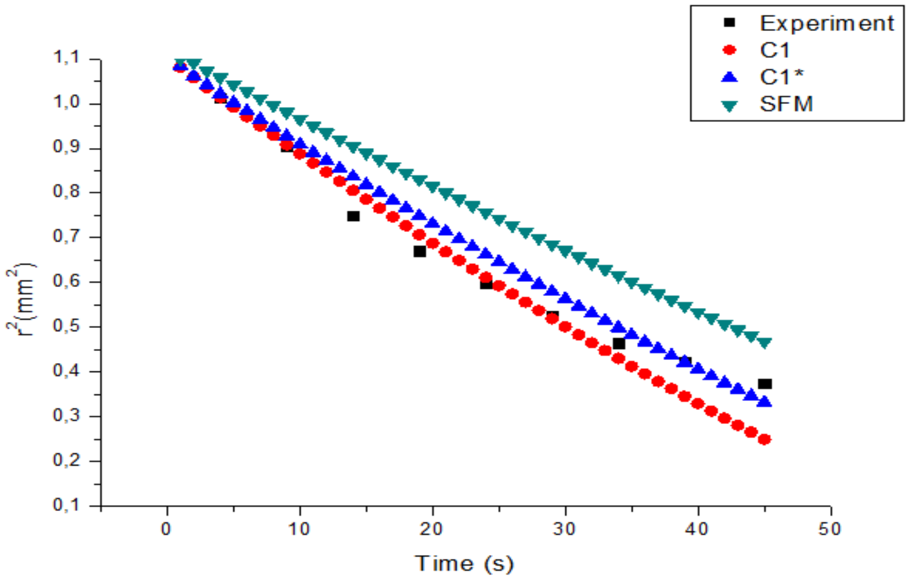

Fig. 4. 2-butanol change in radius square by time (35°C 7 m/s airflow)

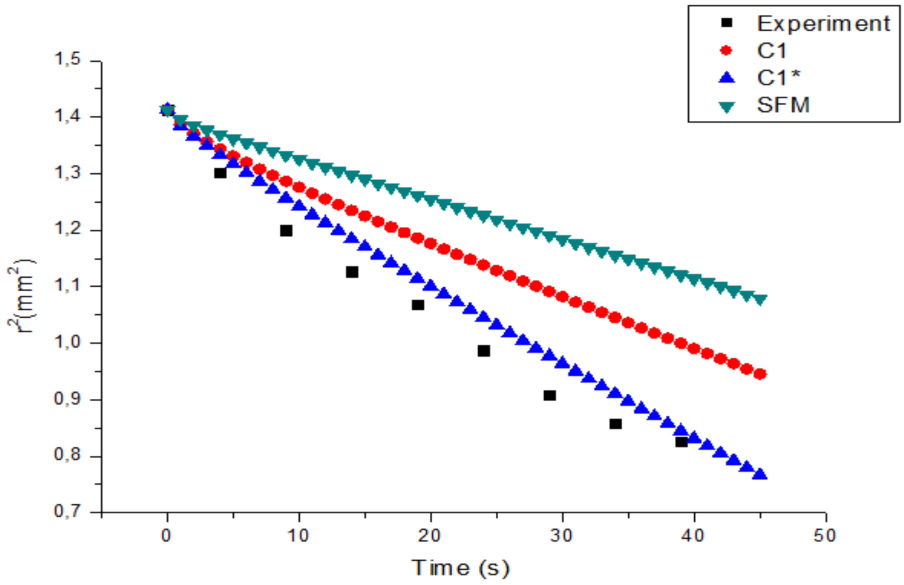

Fig. 5. 2-butanol change in radius square by time (35°C 7 m/s airflow)

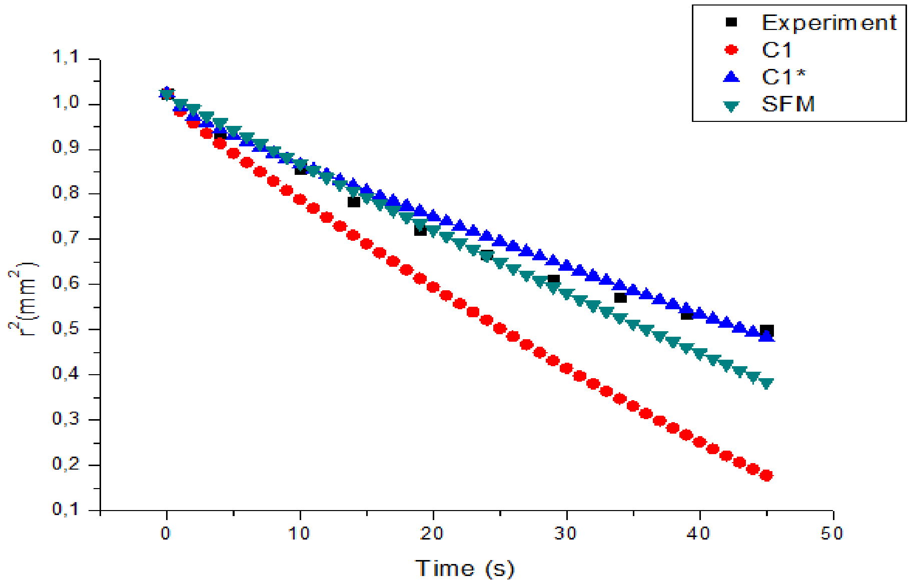

Fig. 6. 2-butanol change in radius square by time (55°C 7 m/s airflow)

Table 3
Apropriate Value of C1 Constant for each experiment (C1*) and the average of C1

C1*	0.1 m/s	0.7 m/s
35°C	-0.025	-0.013
55°C	-0.032	-0.02
C1	0.0225	

Figure 7 to Figure 10 shows the change in temperature by time. By using the same value of C1 and C2, the simulation simultaneously done to evaluate the change in droplet temperature. While having a satisfactory prediction in predicting radius square, the new approach to stagnant film model failed to predict the change in droplet temperature.

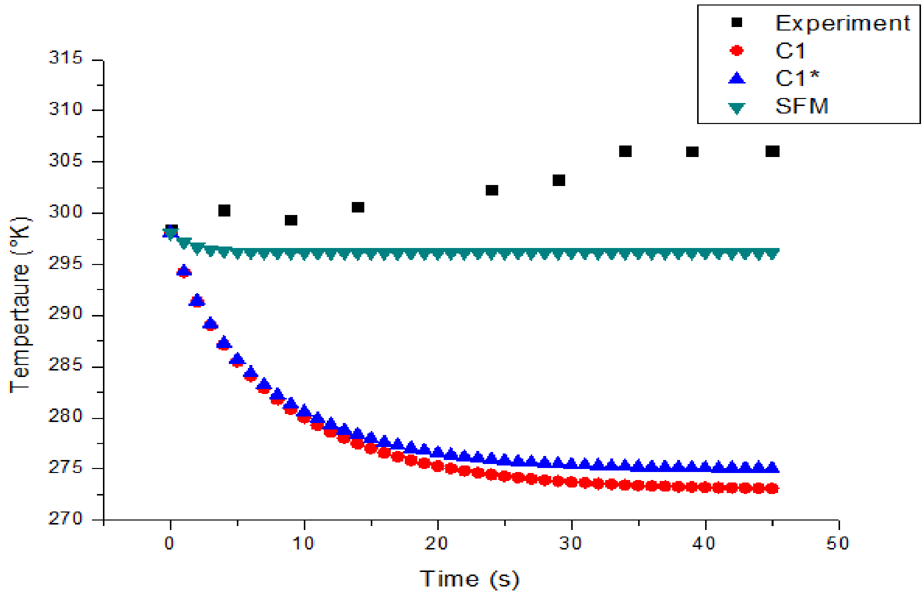

Fig. 7. 2-butanol change in temperature by time (35°C 1 m/s airflow)

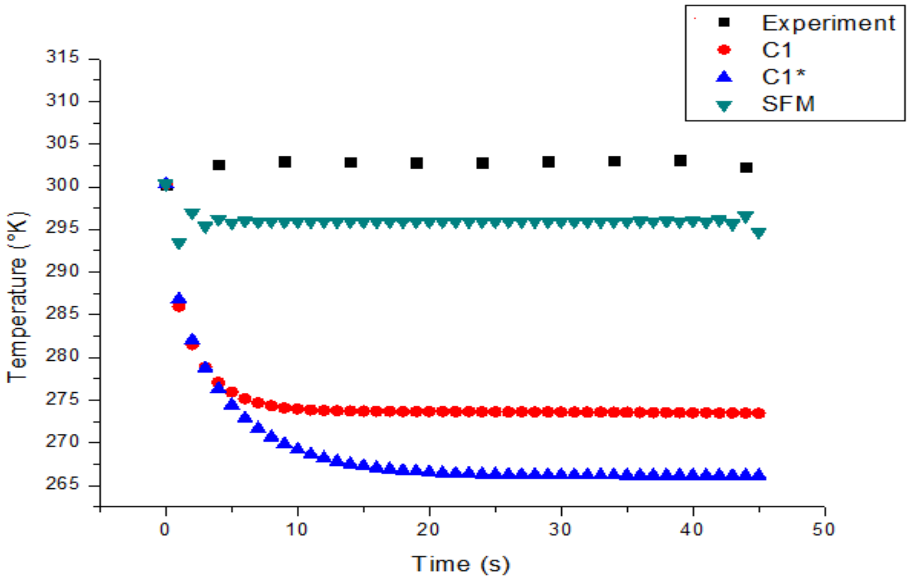

Fig. 8. 2-butanol change in temperature by time (35°C 7 m/s airflow)

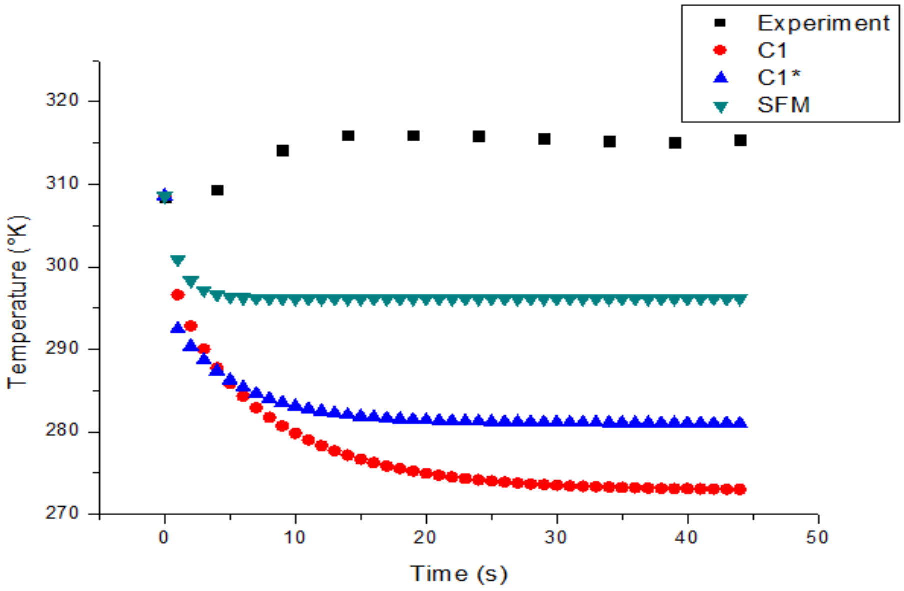

Fig. 9. 2-butanol change in temperature square by time (55°C 1 m/s airflow)

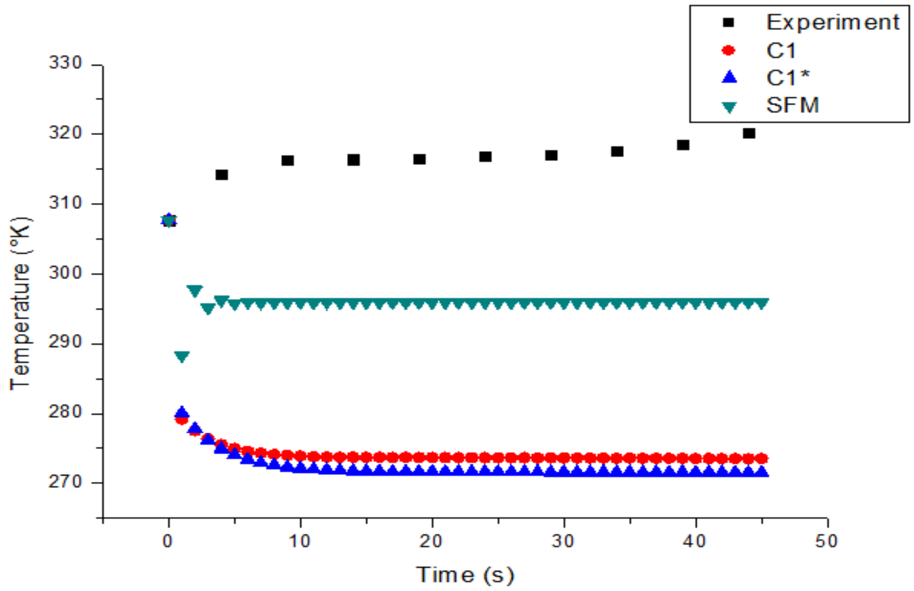

Fig. 10. 2-butanol change in temperature by time (55°C 7 m/s airflow)

While both model having dificulties in predicting change of temperature, the new approach to stagnant film model deviates less on predicting the change in radius with the right amount of C1. Since the value of C1 differs, a further investigation on more parameters and substances is needed in order to create the universal equation value of C1.

4. Conclusions

The value of C1 and C2 in the new approach to stagnant film model was discussed in this paper. Stagnant film is an imaginary film without potential gradient outside of the film. The new approach assumes the thickness of concentration film changes as the heat and mass transfer applies. The conclusions can be obtained as follows

i. The new approach to stagnant film model predicts change in radius better than the original stagnant film model with the right value of C1.
ii. While being better in predicting the change in radius of a droplet evaporation, both models failed to predict the change in temperature.
iii. For 2-butanol, C2 ranges between -4×10^{-8} to -8×10^{-8} with the most appropriate value of -4×10^{-8}.
iv. For 2-butanol, C1 ranges between -0.010 to -0.035 differs for each flow rate and flow temperature. Therefore, the value of C1 must be a function that can be furtherly investigated with the value of another substances.

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