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A new empirical model for calculating solubility of cholesterol in supercritical dioxide carbon

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Abstract
In this research, a new empirical model for calculating solubility of cholesterol in supercritical dioxide carbon has been proposed. The new empirical model included a new parameter is time of staying meat under supercritical CO2, as well as the traditional parameters as pressure and temperature. Multiple linear regression is used to obtain the new empirical model with coefficient correlation of 0.963 and 0.973 for both of static and dynamic methods respectively, as well as the standard error reached 0.014 and 0.00915 respectively, also all parameters have a significant effect on the cholesterol solubility in supercritical CO2 for static and dynamic methods. The results also showed that the cholesterol diffusion coefficient in supercritical CO2 was significantly increased with increasing temperature and reduced with increasing pressure. Values of mass transfer coefficient ranged between 1.3468×10-5 – 3.7756×10-5 m-2s-1 and 6.9177×10-6 - 3.6480×10-5 m-2s-1 for static and dynamic methods respectively.
Key words: supercritical CO2, cholesterol, solubility, meat

1. Introduction

In the last years, the interest has been increased with supercritical fluids especially supercritical CO2 because this technology is readily used in many applications such as extraction of oils and lipids (Chao, et.al.,1991 ; Froning, et.al.,1992), as well as removal of cholesterol from meat (Wehling,1991), egg (Catchpole,et.al.,2009) , milk and butter (Rizvi and Bhasker,1995). In general, the extraction process by using supercritical fluids is faster than traditional methods. Supercritical CO2 is always used commonly in removal cholesterol and extraction oil and caffeine because it is nonflammable, nontoxic, and inexpensive. In addition, it has good critical properties like it is critical pressure and temperature which are 73.8 bar and 31.2 oC respectively (Cheng et al., 2013; Nasri et al., 2014; Baseri et al., 2014 and Huang et al., 2013). Solubility of solutes in supercritical CO2 is an important thermo-physical characteristic. This characteristic is determined by two methods, the first is using theoretical or semi-empirical models depend on state equations such as cubic EoSs which used to calculate of solid solubility in supercritical fluids because of relevant quickness of calculations, in addition to their reliability and flexibility. (Housaindokht et al., 2007; Yazdizadeh et al., 2011; Wang et al., 2014; Su et al., 2013; Asgarpour et al., 2014; Baseri et al., 2013; Ardjman et al., 2014). On the other hand, they are inaccurate for calculating complex process like process with very massy compounds and need sophisticated calculations, as well as knowing solid properties having molar volume, acentric factor critical properties which can be calculated from equations and unable determined experimentally (Garnier et al., 1999; Shojaee et al., 2013).The second is empirical equations like density based equations such as Chrastil model (Chrastil, 1982), Kumar and Johnston model(Kumar and Johnston, 1988), del Valle and Aguilera model (del Valle and Aguilera,1988), Mendez-Santiago and Teja model(Mendez-Santiago and Teja, 2000), Bartle and others model (Bartle et al., 1991), Yu and others model(Yu et al., 1994), Sung and Shim model (Sung and Shim, 1999), Gordillo and others model (Gordillo et al., 1999), Jouyban and others model (Jouyban et al., 2002), Adachi and Lu model (Adachi and Lu, 1983), Garlapati and Madras model (Garlapati and Madras, 2009), Jafari Nejad and others model (Jafari Nejad et al., 2010) and Khansary and others model(Khansary et al., 2015). Modulus of these models are taken depended on minimization of error for empirical equations that are against temperature, pressure and density of supercritical CO2.

Rostamian et al., (2015) proposed a modified Redlich-Kwong model of state for calculating the solubility of many solids (one of them solids is cholesterol) in supercritical CO2, and they have been coupled state equation with the van der Waals zero mixing law. Also, they found that the absolute average relative deviation reached 5.7% for the proposed model. Khansary et al., (2015) proposed new empirical model for calculating solubility of solute supercritical CO2 and compared their proposed model with thirteen published empirical models and they concluded that the proposed model was more accurate in estimation or prediction of solubility compared with other models. All these published empirical models did not take into consideration the effect of staying meat time under supercritical CO2 on cholesterol solubility. So, the present study aimed to propose a new model for calculating solubility of cholesterol in supercritical CO2 including time of staying meat under supercritical CO2, pressure and temperature. In addition, calculation of the cholesterol diffusion in supercritical CO2 and mass transfer coefficient of cholesterol from meat to supercritical CO2.

2.0 Materials and methods

2.1 Supercritical CO_2 system

Supercritical CO_2 system that locally manufactured by AL Rubaiy (2016) had used to removal cholesterol from fresh cow meat as illustrated in figure 1. This apparatus works by two methods, the first is a static method which means that the meat stays under supercritical CO_2 pressure for specific time, when the pressure is reduced, the cholesterol and oil with CO_2 together separate from meat. The second method means the supercritical CO_2 pass via the meat and separates cholesterol and some oil from meat then goes to hunter for separating a part of the cholesterol and oil. The rest of cholesterol and oil move with CO_2 to the cholesterol removal cylinder containing calcium carbonate which absorbs cholesterol only. Then the oil with CO_2 goes to the pump and return to extraction cylinder. The experiment carried out by three supercritical pressures (75, 85 and 95 bar), three temperatures (35, 45 and 55 ^oC) and four staying times (20, 40, 60 and 80 min).

2.2 Cholesterol determination

A 0.1 g has been took from meat sample and it added to 1.9 ml of ethanol then shacked well and put in the centrifugal with 3000 rpm for 15 min. then the filtered liquid is took and added to it 0.25 ml. of ferric chloride, and concentrated H_2SO_4 has been added to the samples and after well shacking was left till cool then the absorbance has been read at wave length at 560 nm. (Alubaidy, 1999).

Figure 1. A photograph of Supercritical CO_2 system

2.3 Mathematical modeling

Chrastil (1982) concluded the following equation which shows the relationship between solids solubility and density of supercritical CO_2, as well as temperature that including three constants (K, A, B). It takes into consideration the equilibrium state between sold materials and supercritical CO_2:

$$S = \rho^K exp\left(\frac{A}{T} + B\right) \quad (1)$$

Where:

S is the solubility of solid materials in supercritical CO_2 (kg m^{-3}).

T is the temperature (K).

ρ is the supercritical CO_2 density (kg/m^3).

K is the constant related with supercritical CO_2

A and B are constants.

Values of constants in equation (1) have been concluded via using solver program in excel 2013 with depending on the average absolute relative deviation (AARD) according to the following equations:

$$AARD = \left(\frac{100}{N}\right) + \sum_{i=1}^{N} \frac{\left|y_{cal.} + y_{exp}\right|}{y_{exp}} \quad (2)$$

$$R^2 = \frac{\sum_{i=1}^{N} (y_{cal.} - \overline{y_{cal.}})^2}{\sum_{i=1}^{N}\left(y_{exp} - \overline{y_{exp}}\right)^2} \quad (3)$$

Where:
N is the data number.
$y_{cal.}$ Is the calculated solubility (kg m^{-3}).
y_{exp} is the experimental solubility (kg m^{-3}).
Mass transfer coefficient was calculated from the following equation (Norhuda and Omar,2009) :

$$K_f = \frac{Sh\, D_{12}}{d_p} \quad (4)$$

K_f is heat transfer coefficient (m^2s^{-1}).
Sh is the Sherwood number.
D_{12} is the cholesterol diffusion coefficient in supercritical CO_2 (m s^{-1})
d_p is the minced meat particle diameter (m).
Sherwood number has been calculated from the following equation (Wakao and Kajuei, 1982):

$$Sh = 2 + 1.1Re^{0.6}Sc^{0.3} \quad (5)$$

Where
R_e is the Reynolds number
S_C is the Schmidt number which relates to the diffusion.
Reynold number was calculated from equation (6):

$$R_e = \frac{ud_p\rho}{\mu} \quad (6)$$

Where
u is the velocity of supercritical CO_2 (m sec^{-1}).
μ is the dynamic viscosity (Pa sec.).
Schmidt number is given by equation (7) (Norhuda and Omar, 2009):

$$S_c = \frac{\mu\, \rho}{D_{12}} \quad (7)$$

Where D_{12} is the cholesterol diffusion coefficient in the supercritical CO_2 (m^2s^{-1}).
The cholesterol diffusion coefficient can be calculated from equation (8) (Catchpole and King, 1994):

$$D_{12} = 5.152 + D_C T_r\left(\rho_r{}^{-2/3} - 0.451\right)\frac{K}{X} \quad (8)$$

D_C is the CO_2 diffusion coefficient at the critical point (m^2 s^{-1})
T_r is the reduced Temperature for supercritical CO_2
ρ_r is the reduced density for supercritical CO_2
K is the correction factor.
T_r and ρ_r have been calculated from the following equations (Wang, et. al., 2015):

$$T_r = \frac{T}{T_C} \quad (9)$$

$$\rho_r = \frac{\rho}{\rho_c} \quad (10)$$

Where
T is the temperature of supercritical CO_2 (^oC).
T_c is the critical temperature of CO_2 (^oC).
ρ_c is the critical density of CO_2 (kg m^{-3}).
ρ is the density of supercritical CO_2 (kg m^{-3}).
Where x value has been calculated from the following equation:

$$x = \frac{\left[1 + 1 + (V_{c2}/V_{c1})^{1/3}\right]^2}{[1 + M_1/M_2]} \quad (11)$$

V_{c1} is the molar volume for CO_2 at critical point (cm^3mol^{-1}).
V_{c2} is the molar volume for CO_2 at cholesterol at critical point (cm^3mol^{-1}).
M_1 is the molecular weight of CO_2 at critical point (g mol^{-1}).
M_2 is the molecular weight of cholesterol(g mol^{-1}).

Correction factor (K) was calculated from the following equation:

$$K = 1 \pm 0.1 \qquad 2 < X$$
$$K = X^{0.17} \pm 0.1 \qquad 2 < X < 10 \qquad (12)$$

CO_2 diffusion coefficient at critical point was calculated from the following equation:

$$D_C = 4.30 \times 10^{-7} + M_1^{1/2} \frac{T_C^{0.75}}{\sum V_1^{2/3} \rho_C} \qquad (13)$$

V_1 is the molar volume at critical point (m^3mol^{-1})
T_c is the critical temperature of CO_2
Coefficient of compressibility (z) was calculated according to the following equation (Marini, 2007) :

$$Z = \frac{PV}{RT} \qquad (14)$$

Where
R is the gases constant (8.314 J mol^{-1} k^{-1}).
T is the temperature (K).
P is the pressure (Pa).
V is volume of CO_2 (m^3mol^{-1})
Dynamic viscosity calculated from equation (15) (Ouyang, 2011):

$$\mu = C_0 + C_1P + C_2P^2 + C_3P^3 + C_4P^4 \qquad (15)$$

μ is the dynamic viscosity (Pa sec.).
P is the pressure (Pa).
Ci is the constants and calculated from the following equation:

$$C_i = d_{i0} + d_{i1}T + d_{i2}T^2 + d_{i3}T^3 + d_{i4}T^4 \qquad (16)$$

T is the temperature (^oC).
Density of supercritical CO_2 was calculated from equation (17) (Ouyang, 2011):

$$\rho = A_0 + A_1P + A_2P^2 + A_3P^3 + A_4P^4 \qquad (17)$$

ρ is the density (kg m^{-3})
P is the pressure (pa)
A_1, A2, A3, A4 are constants and calculated from equation (18):

$$A_i = b_{i0} + b_{i1}T + b_{i2}T^2 + b_{i3}T^3 + b_{i4}T^4 \qquad (18)$$

All constants are illustrated in Ouyang (2011)

3.0 Results and discussion

3.1 The cholesterol solubility and mass transfer coefficient

A multiple regression by enter method has been used for producing the following equation which shows solubility of cholesterol in the supercritical CO_2 using static method:

$$S = -0.00929 - 0.00152T + 0.002046t + 0.000816P \qquad (19)$$

Solubility of cholesterol in the supercritical CO_2 by using dynamic method was illustrated in equation (20):

$$S = -0.0366 - 0.00118T + 0.001532t + 0.001049P \qquad (20)$$

Where: S, T, t, P are solubility (gl^{-1}), Temperature (^oC), staying time of meat under $SCCO_2$ effect (min) and pressure (bar) respectively.

Both equations (19) and (20) were dependent on the Temperature, pressure and staying time of meat under $SCCO_2$ effect. The results showed that the staying time of meat under $SCCO_2$ effect which had a significant effect on the solubility of cholesterol into supercritical CO_2, as well as temperature and pressure. The solubility at temperature of 35 ^oC, pressure of 75 bar and staying time of 80 min. was reached 0.162390008, 0.174647304 and 0.174647355 gl^{-1} by using proposed equation, chrastil equation and practical results respectively, but in the dynamic method, the solubility reached 0.12867128, 0.13395961 and 0.138664403 gl^{-1} respectively at the same conditions. The results showed that increasing temperature led to reduce solubility of cholesterol at a constant pressure. For example, the solubility reached 0.162390008, 0.174647304 and 0.174647355 gl^{-1} respectively by using pressure of 75 bar, temperature of 35 ^oC and staying time of 80 min. by static method as shown in tables (3) and (4). On the other hand, the solubility has been reduced to 0.147191383, 0.136870272 and 0.136870277 gl^{-1} respectively at pressure of 75 bar, temperature of 45 ^oC and staying time of 80 min., while reached to 0.131992758, 0.124560198 and 0.124571788 gl^{-1} respectively at pressure of 75 bar, temperature of 55 ^oC and staying time of 80 min. by using proposed equation, Chrastil equation and practical results.

Table 1. ANOVA table and the constants related with proposed equation at using static method.

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.963002
R Square	0.927374
Adjusted R Square	0.920565
Standard Error	0.01421
Observations	36

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	0.082507154	0.027502	136.2039	2.67064E-18
Residual	32	0.006461463	0.000202		
Total	35	0.088968617			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-0.00929	0.028493676	-0.32597	0.746567	-0.06732787	0.048752	-0.06732787	0.04875157
temperature	-0.00152	0.000290058	-5.23986	9.89E-06	-0.002110691	-0.00093	-0.00211069	-0.000929
time	0.002046	0.000105914	19.31962	3.32E-19	0.001830481	0.002262	0.001830481	0.00226196
pressure	0.000816	0.000290058	2.81211	0.008338	0.000224846	0.001407	0.000224846	0.0014065

Table 2. ANOVA table and the constants related with proposed equation at using dynamic method.

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.973303
R Square	0.94732
Adjusted R Square	0.942381
Standard Error	0.009152
Observations	36

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	0.048195	0.016065	191.8121	1.58427E-20
Residual	32	0.00268	8.38E-05		
Total	35	0.050875			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-0.0366	0.018351	-1.99424	0.054704	-0.073976209	0.000783	-0.073976209	0.00078343
temperature	-0.00118	0.000187	-6.2954	4.63E-07	-0.00155655	-0.0008	-0.00155655	-0.0007955
time	0.001532	6.82E-05	22.45584	3.72E-21	0.001392832	0.001671	0.001392832	0.00167072
pressure	0.001049	0.000187	5.616009	3.31E-06	0.000668602	0.00143	0.000668602	0.00142963

There was a large converge among calculated solubility of cholesterol in $SCCO_2$ from proposed equations 19 and 20, practical results and Chrastil equation. Determination coefficient was high as shown in both tables 3 and 4 and figures 2 and 3. The general form of the proposed equation which describes solubility of cholesterol in the $SCCO_2$ by using static and dynamic methods as follow:

$$S = \mathrm{a} - \mathrm{bT} + \mathrm{ct} + \mathrm{dP} \qquad (21)$$

Table 3. Practical and theoretical cholesterol solubility in super critical carbon dioxide by static method and it is statistical parameters and mass transfer coefficient.

Temperature (°C)	Time (min.)	Pressure (bar)	Solubility (proposed equation)	Solubility (Chrastil equatioin) (gl^{-1})	Practical Solubility (gl^{-1})	R^2	AARD	A	B	k	k f (m^2s^{-1})
35	20	75	0.039616709	0.033545342	0.03354534						3.77567E-05
35	20	85	0.047773457	0.035891055	0.035925693	0.99995	0.040965	-1152.1	-0.72893	0.17796	1.85394E-05
35	20	95	0.055930206	0.038139817	0.038129723						1.34681E-05
35	40	75	0.080541142	0.070354019	0.072071788						3.77567E-05
35	40	85	0.08869789	0.07841199	0.074716625	0.939088	2.443123	-1102.6	-0.72262	0.285507	1.85394E-05
35	40	95	0.096854639	0.086441968	0.086442065						1.34681E-05
35	60	75	0.121465575	0.134313452	0.134313602						3.77567E-05
35	60	85	0.129622324	0.161596584	0.137178841	0.896615	5.944377	-270.88	-3.77471	0.486899	1.85394E-05
35	60	95	0.137779072	0.190827902	0.190891058						1.34681E-05
35	80	75	0.162390008	0.174647304	0.174647355						3.77567E-05
35	80	85	0.170546757	0.183020373	0.180421914	0.983266	0.48012	-287.83	-1.50305	0.123297	1.85394E-05
35	80	95	0.178703505	0.190890833	0.190891058						1.34681E-05
45	20	75	0.024418084	0.031782088	0.031782116						3.64802E-05
45	20	85	0.032574832	0.034355559	0.03354534	0.983245	0.809261	-269.7	-3.70382	0.205002	3.18245E-05
45	20	95	0.040731581	0.036846815	0.036851385						2.67611E-05
45	40	75	0.065342517	0.052584629	0.053425693						3.64802E-05
45	40	85	0.073499265	0.066365311	0.056731738	0.927179	6.185105	-296.45	-5.30977	0.612816	3.18245E-05
45	40	95	0.081656014	0.081813502	0.081813602						2.67611E-05
45	60	75	0.10626695	0.10354534	0.10354534						3.64802E-05
45	60	85	0.114423699	0.109072698	0.112714106	0.932303	1.078976	-265.68	-2.16916	0.136926	3.18245E-05
45	60	95	0.122580447	0.114293843	0.114301008						2.67611E-05
45	80	75	0.147191383	0.136870272	0.136870277						3.64802E-05
45	80	85	0.155348132	0.142729181	0.139338791	0.945287	0.833563	-248.35	-1.80171	0.11036	3.18245E-05
45	80	95	0.16350488	0.148210784	0.148110831						2.67611E-05
55	20	75	0.009219458	0.029573139	0.029578086						3.34552E-05
55	20	85	0.017376207	0.030626595	0.029842569	0.91127	0.88134	-300.09	-3.1021	0.092158	2.5371E-05
55	20	95	0.025532955	0.031605765	0.031605793						1.7986E-05
55	40	75	0.050143892	0.058036016	0.058054156						3.34552E-05
55	40	85	0.05830064	0.064416191	0.059023929	0.897353	3.055677	-308.15	-3.38476	0.274618	2.5371E-05
55	40	95	0.066457389	0.070749326	0.07074937						1.7986E-05
55	60	75	0.091068325	0.095522578	0.09552267						3.34552E-05
55	60	85	0.099225073	0.102571498	0.102531486	0.992696	1.045153	-285.45	-2.48681	0.187458	2.5371E-05
55	60	95	0.107381822	0.109352243	0.112846348						1.7986E-05
55	80	75	0.131992758	0.124560198	0.124571788						3.34552E-05
55	80	85	0.140149507	0.132991314	0.129023929	0.963158	1.028079	-273.06	-2.17837	0.172443	2.5371E-05
55	80	95	0.148306255	0.141057919	0.141057935						1.7986E-05

The results also showed that the solubility of cholesterol was increased with increasing inserted pressure and staying time of meat under supercritical pressure effect. It can be seen from tables 3 and 4 that the solubility reached 0.162390008, 0.174647304 and 0.174647355 gl^{-1} by using proposed equation, Chrastil and practical results respectively at conditions of pressure of 75 bar , temperature of 35 ^oC and staying time of 80 min. by static method, and it has been reduced to 0.147191383, 0.136870272 and 0.136870277gl^{-1} respectively at the conditions (P=75 bar, T=80 min. T=55 ^oC), while at using dynamic method and at the same conditions (P=75 bar, T=80 min. T=55 ^oC) was reached 0.09994775, 0.096750139 and 0.09622796 gl^{-1} by using proposed equation, Chrastil and practical results respectively, also when temperature reduced to 35 ^oC, the solubility reached 0.123468426, 0.116769385 0.116769521 gl^{-1} respectively. on the other hand, when the pressure was 95 bar, temperature of 35 ^oC and staying time of meat under supercritical CO_2 of 80 min. have a significant effect ($p \leq 0.05$) on the cholesterol solubility in the $SCCO_2$ as illustrated in tables 3 and 4 . However, all equations in the published papers that descripted solubility of cholesterol in $SCCO_2$ were dependent on the pressure, density and temperature, but the proposed equation in this study was dependent on pressure, temperature and staying time of meat under $SCCO_2$ effect.

Table 4. Practical and theoretical cholesterol solubility in super critical carbon dioxide by dynamic method and it is statistical parameters and mass transfer coefficient.

Temperature (°C)	Time (min.)	Pressure (bar)	Solubility (proposed equation)	Solubility (Chrastil equatioin) (gl^{-1})	Practical Solubility (gl^{-1})	R^2	AARD	A	B	k	k f (m^2s^{-1})
35	20	75	0.031561835	0.033986145	0.033986146						1.75066E-05
35	20	85	0.042053019	0.036159144	0.036146096	0.995934	0.641609	-266.701	-3.39404	0.163181	9.55331E-06
35	20	95	0.052544203	0.038231269	0.038967254						6.91773E-06
35	40	75	0.062197366	0.074407825	0.07440806						1.75066E-05
35	40	85	0.07268855	0.078794813	0.067267003	0.531565	5.712618	-248.743	-2.60228	0.15083	9.55331E-06
35	40	95	0.083179733	0.08295958	0.082959698						6.91773E-06
35	60	75	0.092832896	0.096448357	0.096448363						1.75066E-05
35	60	85	0.10332408	0.115238001	0.104206549	0.948526	3.851914	-699.157	-2.59061	0.46864	9.55331E-06
35	60	95	0.113815264	0.135237615	0.136561713						6.91773E-06
35	80	75	0.123468426	0.116769385	0.116769521						1.75066E-05
35	80	85	0.13395961	0.138664403	0.128671285	0.968964	2.594935	-661.948	-2.43327	0.452484	9.55331E-06
35	80	95	0.144450794	0.161834367	0.16186398						6.91773E-06
45	20	75	0.019801497	0.025698813	0.025698992						2.3369E-05
45	20	85	0.030292681	0.02932332	0.025258186	0.842561	5.365213	-798.463	-3.02014	0.347384	1.33846E-05
45	20	95	0.040783865	0.033016577	0.033016373						9.41969E-06
45	40	75	0.050437028	0.059464718	0.059464736						2.3369E-05
45	40	85	0.060928212	0.062346013	0.046549118	0.277816	11.31577	32.36028	-3.59419	0.124581	1.33846E-05
45	40	95	0.071419395	0.065055606	0.065062972						9.41969E-06
45	60	75	0.081072558	0.081790824	0.071586902						2.3369E-05
45	60	85	0.091563742	0.085957179	0.085957179	0.998352	8.85045	32.43303	-3.30917	0.130815	1.33846E-05
45	60	95	0.102054926	0.089884065	0.102487406						9.41969E-06
45	80	75	0.111708088	0.09893401	0.100724181						2.3369E-05
45	80	85	0.122199272	0.118483554	0.115447103	0.993094	1.46936	31.93235	-4.96741	0.474773	1.33846E-05
45	80	95	0.132690456	0.139337937	0.139338791						9.41969E-06
55	20	75	0.008041159	0.013400479	0.013400504						3.64802E-05
55	20	85	0.018532343	0.018686052	0.034030227	0.518372	15.06553	-44.681	-8.88504	0.875414	3.18245E-05
55	20	95	0.029023527	0.025196846	0.025170025						2.67611E-05
55	40	75	0.03867669	0.040245599	0.040245592						3.64802E-05
55	40	85	0.049167874	0.049460514	0.059023929	0.863211	5.439689	-26.2128	-6.05274	0.542841	3.18245E-05
55	40	95	0.059659058	0.059533977	0.059464736						2.67611E-05
55	60	75	0.06931222	0.065116389	0.065062972						3.64802E-05
55	60	85	0.079803404	0.073287038	0.08895466	0.671261	5.898386	-26.1141	-4.32607	0.311232	3.18245E-05
55	60	95	0.090294588	0.08150505	0.081505038						2.67611E-05
55	80	75	0.09994775	0.096750139	0.09622796						3.64802E-05
55	80	85	0.110438934	0.108089145	0.113507557	0.962259	1.772087	-26.0586	-3.82573	0.291793	3.18245E-05
55	80	95	0.120930118	0.119414358	0.119414358						2.67611E-05

This may be attributed to increase temperature which leads to huge reduce in density and viscosity of $SCCO_2$, then reduce its efficiency in solubility and cholesterol transfer (Ouyang, 2011). Wang,et.al., (2015) stated that density of $SCCO_2$ increases with increasing pressure at constant temperature. It can be seen from tables 3 and 4 that the solubility was increased with increasing staying time of meat at constant pressure and temperature. For example, solubility reached 0.055930206, 0.038139817 and 0.038129723 gl^{-1} by using proposed equation, Chrastil equation and practical data respectively at pressure of 95 bar, temperature of 35 °C and staying time of 20 min. When staying time increased to 80 min., solubility of cholesterol increased to 0.178703505, 0.140890833 and 0.190891058 gl^{-1} respectively at a constant pressure and temperature , this results applied on both static and dynamic methods .On the other hand , solubility of cholesterol by static method is greater than dynamic method . This may be attributed to mass transfer coefficient by static method was higher than dynamic method as illustrated in tables 3 and 4. For example, the mass transfer coefficient reached 1.34681×10^{-5} m^2s^{-1} by using static method at pressure of 95 bar, temperature of 35 °C and staying time of 80 min., while it reached 6.91773×10^{-6} m^2sec^{-1} by using dynamic method at the same conditions. However, mass transfer coefficient indicates speed of cholesterol transfer toward $SCCO_2$. The results also showed that the values of mass transfer coefficient ranged between 1.3468×10^{-5} – 3.7756×10^{-5} $m^{-2}s^{-1}$ and 6.9177×10^{-6} - 3.6480×10^{-5} $m^{-2}s^{-1}$ for both static and dynamic methods respectively.

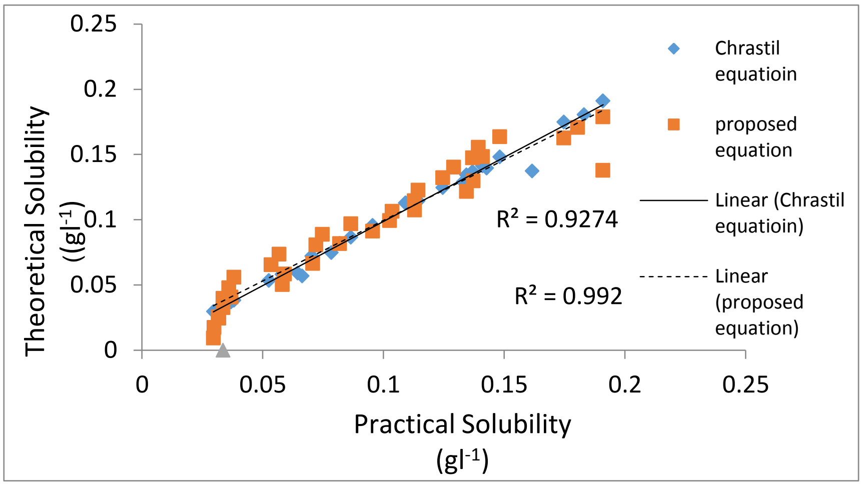

Figure 2. The correlation between practical and theoretical solubility of cholesterol by static method.

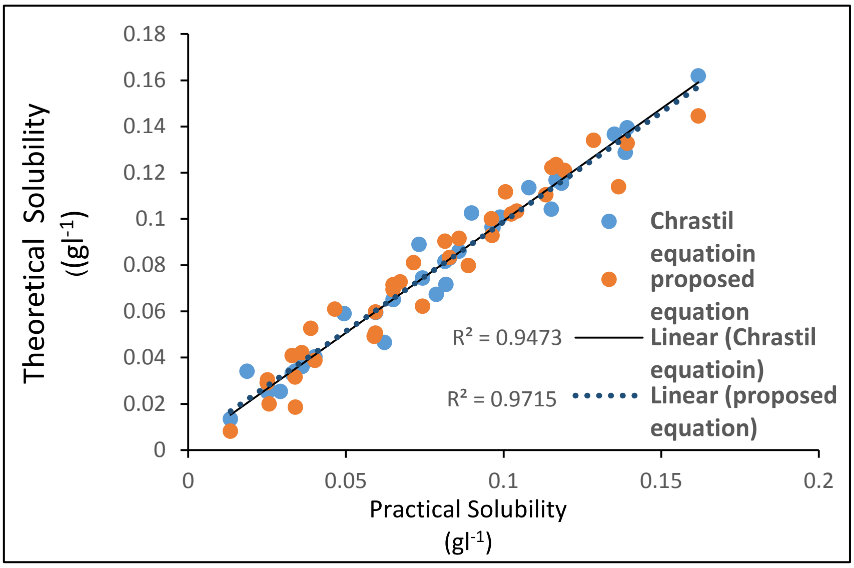

Figure 3. The correlation between practical and theoretical solubility of cholesterol by dynamic method.

3.2 Diffusion of cholesterol in $SCCO_2$:

Figures 4 and 5 illustrate the cholesterol diffusion coefficient at different temperatures (35, 45 and 55 ^oC) and different pressures (75, 85 and 95) by two methods (static and dynamic). The results showed that the cholesterol diffusion coefficient in $SCCO_2$ increased with increasing temperature ,for example the diffusion coefficient reached 3.77567×10^{-5} , 3.64802×10^{-5} and 3.64802×10^{-5} m^2s^{-1} at temperature of 35, 45 and 55 ^oC respectively at pressure of 75 bar by static method, while it reached 1.75066×10^{-5} , 2.33690×10^{-5} and 3.64802×10^{-5} m^2s^{-1} respectively by using dynamic method at the same conditions, the results also showed that the cholesterol diffusion coefficient was reduced with increasing pressure and temperature where diffusion coefficient reached 3.64802×10^{-5} m^2s^{-1} at pressure of 75 bar and temperature of 55 ^oC, also it reached to 3.18245×10^{-5}, 2.67611×10^{-5} m^2s^{-1} at 85 bar and 95 bar respectively by static method , while using dynamic method at 75 bar pressure and 55 ^oC temperature , the diffusion coefficient reached 3.34862×10^{-5} m^2s^{-1} and it reduced to 3.38110×10^{-5} 3.17899×10^{-5} m^2s^{-1} at pressure of 85 and 95 bar respectively, this may be attributed to increase viscosity and density of $SCCO_2$ where it led to reduce diffusion coefficient. Han, et al. (2007) stated that increasing pressure of $SCCO_2$ led to reduce diffusion coefficient of soluble material in $SCCO_2$. Also, the results showed that the diffusion coefficient has been increased with increasing temperature.

Vederman,et al.(2005) found that the cholesterol diffusion coefficient in the $SCCO_2$ at 230, 250 and 270 bar and temperature of 60 ^oC is 2.3×10^{-13} m^2l^{-1} for all pressures in his study and when temperature increased to 70 ^oC , the diffusion coefficient has been increased .

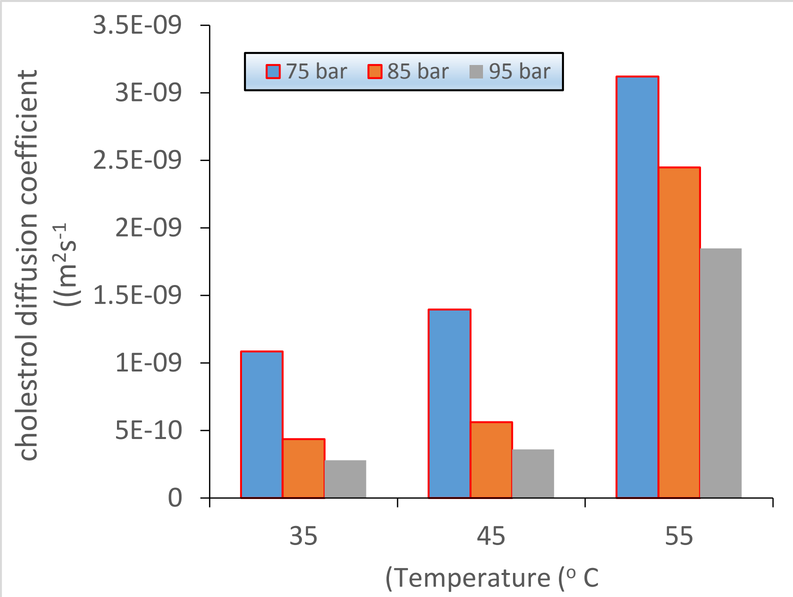

Figure 4. The Cholesterol diffusion coefficient in supercritical carbon dioxide using the static method.

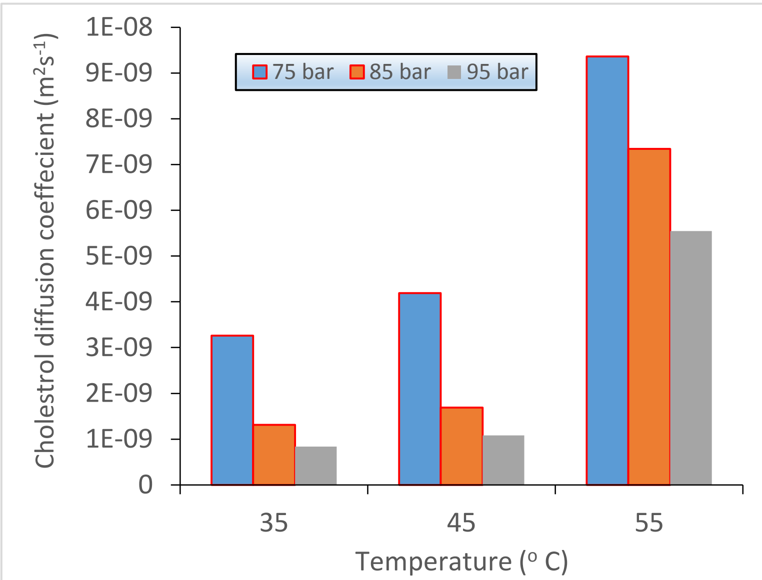

Figure 5. The Cholesterol diffusion coefficient in supercritical carbon dioxide using dynamic method.

4.0 Conclusion

The proposed new empirical model can be used to predict solubility of cholesterol in supercritical dioxide carbon. The difference between static and dynamic method in solubility of cholesterol in supercritical dioxide carbon were significant. Time of staying meat under supercritical dioxide carbon had a huge effect on the solubility of cholesterol in supercritical dioxide carbon, as well as temperature and pressure. The cholesterol diffusion coefficient in super critical CO_2 increased with increasing temperature and reduced with increasing pressure. Mass transfer coefficient in static method was higher than dynamic method.

5.0 Abbreviations

$SCCO_2$**:** supercritical carbon dioxide**.**

CO_2: carbon dioxide**.**

6.0 Acknowledgement

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