An empiric equation for the latent heat of vaporization of moisture in bananas during its isothermal drying

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ABSTRACT

In order to determine the energy needed to artificially dry a product, the latent heat of vaporization of moisture in the product, h_{fg}, must be known. Generally, the expressions for h_{fg} reported in the literature are of the form $h_{fg} = h(T)f(M)$, where $h(T)$ is the latent heat of vaporization of free water, and $f(M)$ is a function of the equilibrium moisture content, M. But expressions of this type contain a simplification because, in this case, the ratio h_{fg}/h would only depend to the moisture content. In this article a more general expression for the latent heat of vaporization, namely $h_{fg} = g(M,T)$, is used to determine h_{fg} for banana. To this end, a computer program was developed which fits automatically about 500 functions, with one or two independent variables, imbedded in its library to experimental data. The program uses nonlinear regression, and classifies the best functions according to the least reduced chi-square. A set of executed statistical tests shows that the generalized expression used in this work given by $h_{fg} = g(M,T)$ produces better results of h_{fg} for bananas than other equations found in the literature.

Keywords: Energy; Agricultural Products; Dried Banana; Heat and Mass Transfer

1. INTRODUCTION

One of the important stages in several productive processes, in the most different areas of human activity, is that regarding the drying of bodies or products constituted by porous materials. As example, drying is used in the following fields: foodstuff, ceramics, pharmaceutical and paper industries. The drying of a wet body can happen in a natural or artificial way. In the case of artificial drying, the most common method for agricultural products is to heat up the air, decreasing its relative humidity, and soon after to transfer it, in a given velocity, for the ambient in which it is placed in contact with such product. Then, there is a continuous process of transfer of heat from air to inside the body. Simultaneously, there is transfer of moisture from the interior of the body to its surface, and from the surface to the drying air, in the form of vapor.

In several studies on artificial drying of a product, it is observed that the determination of the amount of energy requested in the process depends, among several factors, on the latent heat of vaporization, h_{fg}, of water in the product. In addition, in the determination of the apparent thermal diffusivity to describe the heat transfer from air to inside the product, h_{fg} is required [1-11]. In some works, latent heat of vaporization is neglected to describe heat transfer from air to inside product during the drying process [12]. In several works, when researchers do not know h_{fg} in given drying condition, they use latent heat of vaporization of free water, h [1,4,7,10]. But h_{fg} in general is significantly different of the latent heat of vaporization h of free water, and it is dependent on the studied product. So, many researchers have conducted studies with objective of determining expressions for the calculation of h_{fg} for several products during the drying. Brook and Foster [13], cited by Brooker *et al.* [14], determined expressions for the calculation of h_{fg} for several products, using experimental data, presupposing that the relation h_{fg}/h for a given product could be written through a function which depends only of the moisture content of the product.

The expression proposed by Brook and Foster [13] is used in works about drying simulations of agricultural products as, for example, in References [15,16]. Al-Mahasneh *et al.* [17] studied moisture sorption thermodynamics of defatted sesame meal and they found good result admitting that the ratio h_{fg}/h depends only on

moisture content. Prado and Sartori [18] also used the general expression proposed by Brook and Foster [13] to study simultaneous heat and mass transfer in packed bed drying of seeds having a mucilage coating. Corrêa *et al.* [19] modified the function h_{fg}/h proposed by Brook and Foster [13], and they fitted the modified function to the data obtained for corn. Kaleemullah and Kailappan [20] determined an expression for the calculation of h_{fg} for red chillies using experimental data obtained for this product. In these works aforementioned, the dependence of the ratio h_{fg}/h with the temperature of the product was not considered.

The objective of this article is to investigate the dependence of the ratio h_{fg}/h with the temperature of the drying air for a given product, and to verify if that dependence is significant in the determination of an expression for h_{fg}. In addition, it was studied a way of including such dependence in the determination of an empiric expression for the calculation of h_{fg} for bananas. In this study, the obtained expression was compared with other available ones in the literature.

2. MATERIAL AND METHODS

In order to obtain an expression for the calculation of the latent heat of vaporization, h_{fg}, of the water in a product, usually the Clausius-Clapeyron's equation is used (see, for example, Smith *et al.* [21]), supposing that the ideal gas equation can be applied to the vapor, being neglected the volume of water in the liquid phase. A usual procedure in the solution of the Clausius-Clapeyron's equation consists in the integration of this equation considering h_{fg} as a constant value between two given states. For free water, the latent heat of vaporization, h, is obtained with the same previous procedure, being substituted the partial pressure of water vapor, P_v, by the partial pressure of water vapor at saturation, P_{vs}. In this way, observing that $P_v = \Phi P_{vs}$, where Φ is the relative humidity of the air, and comparing the expression obtained for h_{fg} with the expression obtained for h, both in the same temperature band, we write (see, for example, Brooker *et al.* [14]):

$$\frac{h_{fg}}{h} = \frac{\ln\left(\Phi_1 P_{vs1}\right) - \ln\left(\Phi_2 P_{vs2}\right)}{\ln P_{vs1} - \ln P_{vs2}}. \qquad (1)$$

If Φ and P_{vs} are determined for the states 1 and 2, the ratio h_{fg}/h, given by **Eq.1**, is known. In this paper, the relative humidity of the air, Φ, will be determined by interpolation of the Modified-Oswin equation fitted to the experimental data of banana, and it was made by [22]:

$$\frac{1}{\Phi} = \left(\frac{16.68 - 0.1212T}{100M}\right)^{0.9020} + 1 \qquad (2)$$

where T is the temperature (˚C), Φ is the relative humidity of the air (decimal) and M is the equilibrium moisture content (decimal, dry basis). Given M and T, the relative humidity of the air, Φ, can be determined from **Eq.2**.

The partial pressure of water vapor at saturation can be determined from, for example, experimental data available in Brooker *et al.* [14], or in Smith *et al.* [21]. These data could be used in the fit, for example, of Antoine's equation. However, the expression for P_{vs} was obtained using Riedel's equation [23,24], because that equation presents better indicators of fit than Antoine's equation. In this paper, the parameters of Riedel's equation were obtained through non-linear regression using the available data in Brooker *et al.* [14], between 0 and 85˚C. Thus, using LAB Fit Curve Fitting Software V. 7.2.48 (www.labfit.net), the obtained equation for P_{vs} is given by the following way:

$$P_{vs} = e^{\left[49.20 - 6643/(T+273.15) - 4.522\ln(T+273.15)\right]}, \qquad (3)$$

where P_{vs} is obtained in kPa when T is given in ˚C. For the mentioned fit, it was obtained the determination coefficient $R^2 = 1.000000$ and reduced chi-square $\chi^2_{red} = 3.78016 \times 10^{-6}$ (almost perfect fit). The form of **Eq.3** results of the integration of Clausius-Clapeyron's equation combined with the ideal gas equation applied to the vapor and the supposition that the latent heat of vaporization of free water is linear function of the temperature.

With **Eqs.2** and **3**, Φ and P_{vs} can be determined for specified values of M and T, and it makes possible to determine the ratio h_{fg}/h through **Eq.1**. On the other hand, an expression for the latent heat of vaporization of free water is given by [14]:

$$h(T) = 2503 - 2.386T, \qquad (4)$$

where h is obtained in kJ·kg^{-1} when the temperature is given in ˚C.

In works about determination of latent heat of vaporization of water in a given product, it is common to admit that the ratio h_{fg}/h, in a given temperature interval, only depends on the moisture content of the product. Brook and Foster [13] proposed the following equation:

$$\frac{h_{fg}}{h} = 1 + Ae^{BM}, \qquad (5)$$

where the parameters A and B are determined by curve fitting. Corrêa *et al.* [19] proposed a modification in **Eq.5**:

$$\frac{h_{fg}}{h} = 1 + Ae^{BM^C}. \qquad (6)$$

Having **Eq.4**, and knowing the parameters of **Eqs.5** and **6**, the last two equations can be rewritten to calculate

latent heat of vaporization of water in a product of the following way:

$$h_{fg} = (2503 - 2.386T)(1 + Ae^{BM}) \qquad (7)$$

and

$$h_{fg} = (2503 - 2.386T)\left(1 + Ae^{BM^C}\right). \qquad (8)$$

Obviously, in **Eqs.7** and **8** it is supposed that the latent heat of vaporization of water in the product is given by a function expressed by two other, with separation of variables, in the form:

$$h_{fg} = h(T)f(M). \qquad (9)$$

In this paper, it was investigated if a more general function, without the previous supposition of separation of variables, given in the form expressed by **Eq.10**, describes the latent heat of vaporization of water in a product better than **Eq.9**:

$$h_{fg} = g(M, T) \qquad (10)$$

The procedure used in the investigation for bananas involved five levels for the equilibrium moisture content, M (0.10; 0.15; 0.20; 0.25 and 0.30 db), and four levels for the temperature, T (10˚C; 20˚C; 30˚C and 40˚C). The calculation of the ratio h_{fg}/h through **Eq.1**, for a given equilibrium moisture content, M, in a specified temperature, T, presupposes the knowledge of the relative humidity of the air, Φ, in two states, named 1 and 2. Thus, the relative humidity of the air was calculated, through **Eq.2**, in a state 1, with $T_1 = T + 1$˚C, and in a state 2, with $T_2 = T - 1$˚C. The two states around T could be characterized by other values, as 0.5˚C, for example, instead 1˚C. However, the chosen band, defined by 1˚C, produces the same results that the band defined by 0.5˚C and, then, the first band was used in the calculations. The partial pressure of vapor at saturation was calculated through **Eq.3** and this makes it possible to calculate the ratio h_{fg}/h using **Eq.1**. Then, the value of h_{fg} could be determined for each M and T, since $h(T)$ can be calcu-

lated by the **Eq.4**. Thus, through curve fit, the parameters *A* and *B* of **Eq.7** could be determined, or the parameters *A*, *B* and *C* of **Eq.8**. The analysis of the results for the points (M, T, h_{fg}/h) could indicate if the consideration of constant value for c/h, with respect to the temperature, is correct or not. If such consideration is not correct, the determination of another expression can be tried for h_{fg}, proposing a more general function of M and T. For such, the "Finder" option of LAB Fit® software was used. This option fits, in an automatic way, about 500 compact functions of one and two independent variables contained at its library to the experimental data. This tool was developed by first two authors of this paper and it was incorporated to LAB Fit® since version 7.2.18. The main characteristic of "Finder" is to determine empiric equations seeking to the description of experimental data. "Finder" classifies the best fitted functions through least reduced chi-square. When the expression for h_{fg} is determined through "Finder", a comparison between this expression and those expressions obtained by fittings of **Eqs.7** and **8** will be made. Such comparison will be accomplished with base in the following statistical tests: coefficient of determination, reduced chi-square and t-Student test.

3. RESULTS AND DISCUSSION

For the specified values for temperature and equilibrium moisture content in the banana, **Table 1** could be set up, which indicates the relative humidity of the air, Φ, calculated through **Eq.2**.

On the other hand, using the **Eq.3**, the partial pressure of water vapor at saturation could be determined, in the neighborhoods of each specified temperature: P_{vs1} ($T_1 = T + 1$˚C) and P_{vs2} ($T_2 = T - 1$˚C). The results are shown in **Table 2**.

With the results obtained in **Tables 1** and **2**, **Eq.1** can be used for determination of the ratio h_{fg}/h for the values of the temperature and moisture content previously specified, and it resulted in **Table 3**.

Table 1. Relative humidity of the air, Φ, obtained through **Eq.2** for banana, in the neighborhoods of the established temperatures.

	T (˚C)							
	10		20		30		40	
M (db)	2	1	2	1	2	1	2	1
	9	11	19	21	29	31	39	41
0.10	0.4012	0.4046	0.4189	0.4226	0.4383	0.4424	0.4599	0.4644
0.15	0.4913	0.4948	0.5096	0.5134	0.5294	0.5336	0.5510	0.5556
0.20	0.5559	0.5594	0.5739	0.5776	0.5932	0.5972	0.6140	0.6184
0.25	0.6049	0.6083	0.6222	0.6258	0.6407	0.6446	0.6605	0.6646
0.30	0.6435	0.6467	0.6600	0.6635	0.6776	0.6813	0.6964	0.7003

Table 2. Partial pressure of water vapor at saturation obtained through **Eq.3**, in the neighborhoods of the established temperatures.

T (˚C)	10	20	30	40
1: P_{vs1} (kPa)	1.3158	2.4914	4.5004	7.7923
2: P_{vs2} (kPa)	1.1511	2.2014	4.0126	7.0043

Table 3. Ratio h_{fg}/h calculated through **Eq.1** for banana.

	T (˚C)			
	10	20	30	40
0.10	1.0631	1.0711	1.0812	1.0913
0.15	1.0531	1.0600	1.0689	1.0780
0.20	1.0469	1.0519	1.0586	1.0670
0.25	1.0419	1.0466	1.0529	1.0580
0.30	1.0371	1.0427	1.0475	1.0524

An observation of **Table 3** indicates that the dependence among h_{fg}/h and the temperature exists for given moisture content. For moisture content equal to 0.10, for example, the percentile discrepancy of h_{fg}/h between 10 e 40˚C is of, approximately, 2.65%. Then, it is evident the introduction of a systematic error when such ratio is described by **Eq.5** or **6**. This can be visualized by the fitting, for example, of **Eq.5** to the data of **Table 3**, as shown in **Figure 1**. **Figure 1** shows that all the points involving the temperatures 30˚C and 40˚C are located above of fitted surface while the points involving the temperatures 10˚C and 20˚C are below.

On the other hand, the latent heat of vaporization of free water can be obtained through **Eq.4**, and it is shown in **Table 4**.

Once obtained the values of the ratio h_{fg}/h (**Table 3**) and h (**Table 4**), the latent heat of vaporization of moisture in the banana, h_{fg}, can be obtained by multiplication of the two values, and it is shown in **Table 5**.

An observation of **Table 5** makes it possible to say: the bigger the equilibrium moisture content of banana is, the more h_{fg} approximates the value of h. On the other hand, comparing the data of **Table 4** with the data of **Table 5**, it can be noticed that a considerable error is made when substituting h for h_{fg}. The smallest error between h_{fg} and h is 3.6% (T = 10˚C; M = 0.30), and the bigger is 8.4% (T = 40˚C; M = 0.10).

The fit of **Eq.7** to the data of **Table 5** gives the expression:

$$h_{fg} = (2503 - 2.386T)(1 + 0.0991e^{-2.753M}) \qquad (11)$$

with h_{fg} in kJ·kg^{-1}; T in ˚C and M decimal. **Eq.11** involves four parameters, although two have only been
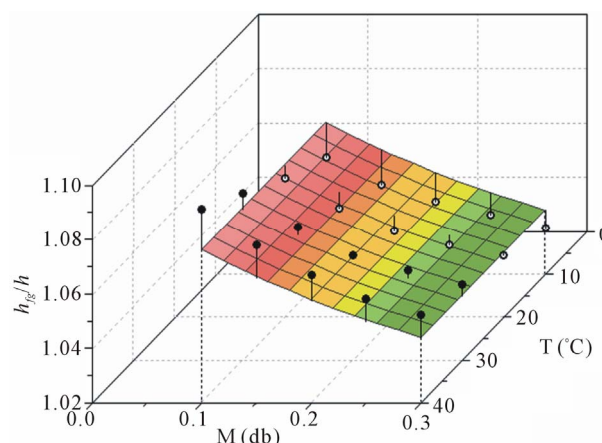
Figure 1. **Eq.5** fitted to data of **Table 3**. The full circles represent experimental points above or on the surface, and the empty circles below it. Each vertical line gives an idea of the distance between the experimental point and the surface.

Table 4. Latent heat of vaporization for free water, h, obtained by **Eq.4**.

T (˚C)	10	20	30	40
h (kJ·kg^{-1})	2479	2455	2431	2408

Table 5. Latent heat of vaporization of moisture in banana, h_{fg}, (kJ·kg^{-1}).

M (db)	T (˚C)			
	10	20	30	40
0.10	2635	2630	2628	2628
0.15	2611	2602	2598	2596
0.20	2595	2582	2573	2569
0.25	2583	2569	2560	2548
0.30	2571	2560	2546	2534

determined by curve fitting in the present paper. About the fit, the following results are presented for the accomplished statistical tests. With respect to the reduced chi-square, it was obtained $\chi^2_{\text{red}} = 448.92$. For the coefficient of determination, it was obtained $R^2 = 0.756869$. For t-Student test, it was obtained $P(t) = 0$ for two determined parameters. Details on these statistical tests can be obtained, for example, in Bevington and Robinson [25] or in Taylor [26]. A plot for the function $h_{fg} = (M,T)$, given by **Eq.11**, is presented in **Figure 2**.

For **Eq.8** fitted to the data of **Table 5**, it was obtained:

$$h_{fg} = (2503 - 2.386T)\left(1 + 0.1936e^{-2.420M^{0.4156}}\right) \qquad (12)$$

with h_{fg} in kJ·kg^{-1}, T in ˚C and M decimal. **Eq.12** involves five parameters, although three have only been
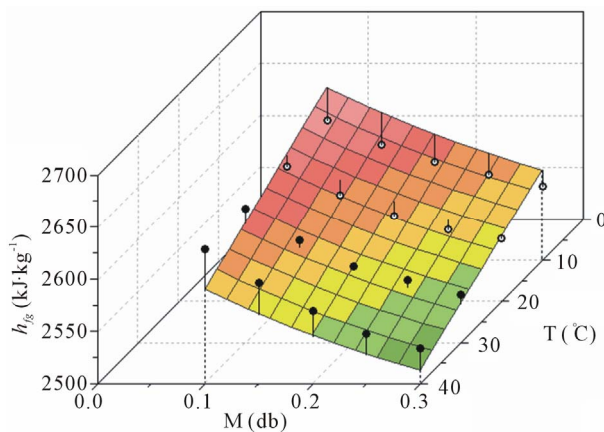
Figure 2. Plot of $h_{fg}(M,T)$ obtained by the proposed model through **Eq.11**. The full circles represent experimental points above or on the surface, and the empty circles below it. Each vertical line gives an idea of the distance between the experimental point and the surface.

determined by curve fitting in the present paper. With respect to the statistical tests, it was obtained $R^2 = 0.760549$ and $\chi^2_{red} = 467.58$. The t-Student test for the first parameter indicates that the probability that this parameter is zero is 74.8%. The second parameter has a probability equal to 19.0%, and the third, 71.2%. The plot of the function $h_{fg}(M,T)$, given by **Eq.12**, is shown in **Figure 3**.

From statistical indicators χ^2_{red} and R^2 we can't conclude that **Eq.12** is better than **Eq.11** to describe data of **Table 5**. In addition, three parameters of **Eq.12**, determined by curve fitting, have a considerable probability of being zero, in spite of the obtained values. This means that the model given by **Eq.12** should be rejected as expression for the calculation of the latent heat of vaporization of water in banana. On the other hand, the fit which resulted in **Eq.11** has very bad statistical indicators, and this equation should also be rejected as expression for the calculation of latent heat of vaporization of water in banana.

As the inspection of **Table 3** indicates a considerable dependence between the ratio h_{fg}/h and the temperature, functions of the type suggested by Brook and Foster [13], given by **Eq.9**, with separation of variables, cannot be the more adapted to express the latent heat of vaporization of water in banana.

Using LAB Fit®'s Finder for the data of **Table 5**, the software related the best functions among the existent

ones in its library. The one that best represents the data of **Table 5** is the function identified by the order number given by 450:

$$f = A\, M^{(B+CT)} + DT \,. \qquad (13)$$

where A, B, C, and D are the parameters of the fit.

After fit of this function to the data, it was obtained:

$$h_{fg} = 2529.1 M^{\left(-1.782\times10^{-2}-3.570\times10^{-4}T\right)} - 2.386T \qquad (14)$$

where h_{fg} is obtained in kJ·kg^{-1} when M is decimal and T is given in °C. **Eq.14** involves four parameters, all them determined by curve fitting in this paper. Statistical indicators to the nonlinear regression of this function were obtained as it follows: $R^2 = 0.996725$ and $\chi^2_{red} = 3.514$. In this fit, all the parameters are significant because, for all them, t-Student test is zero: $P(t) = 0$. The indicators of the quality of this last fit are much better than those referring ones to **Eqs.11** and **12** and, for this reason, **Eq.14** can be considered as an option for the determination of latent heat of vaporization of water in banana. The plot of $h_{fg}(M,T)$, given by **Eq.14**, is presented in **Figure 4**.

The idea of the precision of a result obtained by **Eq.14**, in comparison to the corresponding value in **Table 5**, can be given performing the calculation of h_{fg} with $M = 0.10$ and $T = 20$°C, for example. For such values of M and T, it is determined $h_{fg} = 2631$ kJ·kg^{-1} (**Eq.14**) and $h_{fg} = 2630$ kJ·kg^{-1} (**Table 5**), and this means that the two values have a percentile discrepancy of only 0.04%.

Naturally, the more precise the results obtained by **Eq.2** for Φ are, the better will be the results obtained by **Eq.14** for h_{fg}.

For the determination of the uncertainty of a value obtained through fitted function, the covariance matrix must be known, and this matrix also is given by LAB Fit® software (see **Eq.15**).

With the covariance matrix known, the uncertainty of a value calculated by **Eq.14** is determined by error propagation [27]:

$$\sigma_{h_{fg}} = \sqrt{\sum_{j=1}^{n}\sum_{k=1}^{n} \frac{\partial f}{\partial z_j} \cdot \frac{\partial f}{\partial z_k} \operatorname{cov}\left(z_j, z_k\right)}, \qquad (16)$$

where f is given by **Eq.13**, n is the number of fitted parameters, and $\operatorname{cov}(z_j,z_k)$ is the covariance between the parameters z_j and z_k. In **Eq.15**, the element (1,1) is $\operatorname{cov}(A,A)$, the element (1,2) is $\operatorname{cov}(A,B)$, and so on. Then, performing the calculation of h_{fg} again, with $M = 0.10$

$$\operatorname{cov} = \begin{bmatrix} 1.925\times10^{1} & 4.240\times10^{-3} & -1.336\times10^{-4} & -6.400\times10^{-1} \\ 4.240\times10^{-3} & 9.848\times10^{-7} & -3.105\times10^{-8} & -1.407\times10^{-4} \\ -1.336\times10^{-4} & -3.105\times10^{-8} & 1.177\times10^{-9} & 5.318\times10^{-6} \\ -6.400\times10^{-1} & -1.407\times10^{-4} & 5.318\times10^{-6} & 2.548\times10^{-2} \end{bmatrix} \qquad (15)$$

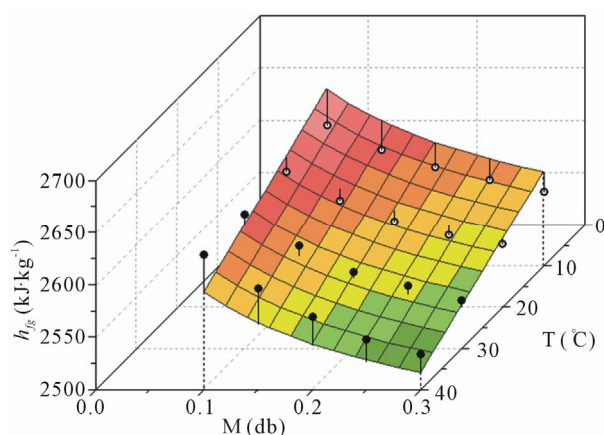**Figure 3.** Plot of $h_{fg}(M,T)$ obtained by the proposed model through **Eq.12**. The full circles represent experimental points above or on the surface, and the empty circles below it. Each vertical line gives an idea of the distance between the experimental point and the surface.
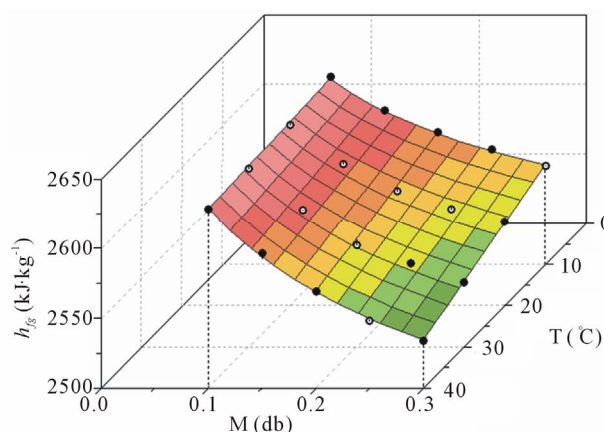

Figure 4. Plot of $h_{fg}(M,T)$ obtained by the proposed model through **Eq.14**. The full circles represent experimental points above or on the surface, and the empty circles below it.

and $T = 20°$C, the complete result obtained by **Eq.14**, including uncertainty calculated by error propagation, is:

$$h_{fg} = (2631.0 \pm 1.9)\,\text{kJ}\cdot\text{kg}^{-1} \tag{17}$$

with a probability of 95.4%.

4. CONCLUSIONS

The analysis of the obtained results for banana, in the temperature band of 10°C up to 40°C and moisture content between 0.10 and 0.30 (db) makes it possible to affirm:

1) As the ratio h_{fg}/h depends on the temperature, for given moisture content, functions of the type of **Eq.10** are more suitable than those given by **Eq.9** for the determination, by curve fitting, of an empiric expression for the latent heat of vaporization of water in banana.

2) For banana in drying process, the latent heat of va-

porization h_{fg} decreases with the increase of the moisture content and the increase of the temperature.

3) The statistical indicators of the fit which resulted in **Eq.13** suggest that such equation is a good option for the determination of the latent heat of vaporization of the analyzed product.

4) The obtained results for banana suggest that the proposed methodology in this paper can constitute in a good alternative for the determination of empiric expressions for the latent heat of vaporization of water in another products.

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