Latent heat of vaporization for selected foods and crops

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Cenkowski, S., Jayas, D.S., and Hao, D. 1992. **Latent heat of vaporization for selected foods and crops**. Can. Agric. Eng. 34:281-286. The equation for latent heat of vaporization was established based on published equilibrium moisture content curves for main crops and selected foods. For moisture content (mc) above 0.2 db, there is little difference between the heat of vaporization from the grain kernels, $h_{fg}*$, and that of free water, h_{fg}. Below 0.2 db, this difference increases significantly for grains such as corn and rice. For the other grains (wheat, barley, bean, peanut kernel, soybean, sorghum), the ratio of $h_{fg}*/h_{fg}$ increases at moisture contents below 0.12 db. There is a significant difference in $h_{fg}*/h_{fg}$ results between durum wheat and soft or hard wheat. The latent heat of vaporization of free water is not significantly different from the latent heat of vaporization of water for celery, cloves, and eggs above 0.10 mc db and above 0.15 mc db for chamomile tea and horse radish. The $h_{fg}*/h_{fg}$ ratios for starchy gels are 1.35 to 1.50, which were the highest of the tested crops and foods, for the moisture range between 0.11 and 0.16 db.

L'équation de la chaleur latente de vaporisation a été établie à partir des courbes connues d'humidité d'équilibre pour des cultures principales et des aliments choisis. Pour une teneur en humidité au-dessus de 0,2 db, il y avait peu de différence entre la chaleur dégagée par la vaporisation de l'amande du grain, $h_{fg}*$, et celle de l'eau libre, h_{fg}. En dessous de 0,2 db, cette différence augmente de manière importante pour les grains de maïs et de riz. Pour ce qui est des autres grains (blé, orge, tofu, arachide, soja, sorgho), le rapport $h_{fg}*/h_{fg}$ augmente lorsque la teneur en humidité est inférieure à 0,12 db. On remarque une différence importante dans les résultats de ce rapport entre le blé dur et le blé tendre ou blé vitreux. La chaleur latente de vaporisation de l'eau libre n'est pas très différente de celle de vaporisation de l'eau contenue dans le céleri, les clous de girofle et les oeufs lorsque l'humidité qu'ils contiennent dépasse 0,10 db, et de l'eau contenue dans la camomille et le raifort lorsque leur teneur en humidité dépasse 0,15 db. Les rapports $h_{fg}*/h_{fg}$ les plus élevés, soit de 1,35 à 1,50, ont été obtenus pour les gelées amylacées dont la teneur en humidité varie de 0,11 à 0,16 db.

INTRODUCTION

The accuracy of predictions of drying processes using mathematical models is highly dependent on the completeness of the mathematical model and the empirical relationships used to describe heat and mass transfer phenomena of a drying product. One such relationship which has a significant influence on computed results is the latent heat of vaporization of water from the drying product. Its mathematical relationship is required so that it can be incorporated into a simulation model.

Moisture is held in hygroscopic materials by physical and chemical forces. The exact mechanism which affects the holding of water in biological materials is not fully understood. Sorption, solution, hydration, chemical combination and capillarity are the factors which influence the bonding mechanism of water to the product. Generally, it is thought that above 12% moisture content dry basis (db), there is little difference between the heat of vaporization of starchy grain, $h_{fg}*$, and that of free water, h_{fg} (Boyce 1965). It is believed that at moisture contents of 12 to 14% (db) or greater, depending on the product, vaporization of moisture from grain involves the removal of free water (Johnson and Dale 1954). Lowering the moisture content to less than 12% dry basis increases the amount of energy required to remove water from the product, partially due to the greater resistance to moisture movement from the interior to the surface of the product.

Johnson and Dale (1954) developed a method for directly measuring the amount of heat required to evaporate moisture during the drying process at different temperatures and varying initial grain moisture contents. Their results indicate that, for wheat and shelled corn having 14% moisture content db, the heat required for vaporization of moisture was about 1.06 times that for the vaporization of free water. At the moisture content of 10%, the latent heat of vaporization was about 1.15 to 1.20 times that for free water.

The latent heat of vaporization of the product can be determined from the equilibrium moisture content data (Gallaher 1951; Sutherland et al. 1971; Bala and Woods 1984). A study of the equilibrium moisture data for different cereals indicates that the latent heat of vaporization of the moisture in the grain would be similar for kernels of approximately the same dimensions (Boyce 1965). Based on the above statements, Boyce (1965) and Ingram (1976) calculated $h_{fg}*$ for barley using a relationship for wheat given by Gallaher (1951).

The need for mathematical relationships capable of predicting heat of vaporization using sorption isotherms to solve problems occurring during food preservation by dehydration, such as the prediction of drying times and of shelf life of a dried product in a packaging material, or the prediction of equilibrium conditions after mixing products with different water activities, has been pointed out by Labuza (1968) and Cenkowski et al. (1990).

Because only limited work has been done on the determination of the heat of vaporization for crops and foods, the objective of this work is to develop mathematical relation-

ships for estimating the heat of vaporization for main crops and selected foods.

METHOD

The change of state from liquid to vapor form at constant temperature and pressure is expressed by Clapeyron's equation (Rogers and Mayhew 1986):

$$\frac{dP}{dT_s} = \frac{h_g - h_f}{T_s(v_g - v_f)}$$ (1)

where:
P = pressure (Pa),
T_s = absolute temperature at saturation point (K),
h = specific enthalpy (J/kg), and
v = specific volume (m³/kg).

The subscript f refers to the saturated liquid state and the subscript g refers to the saturated vapour.

Assuming ideal gas behaviour of the vapour phase, the specific volume of saturated vapour, v_g, can be calculated using the perfect gas equation:

$$v_g = \frac{R T_s}{P}$$ (2)

where R is the gas constant for water vapour (462 J·kg⁻¹·K⁻¹)

The specific volume of saturated liquid, v_f, is very small compared to v_g and can be ignored (Othmer 1940). The difference between h_g and h_f in Eq. 1 describes the latent heat of vaporization and is usually expressed by h_{fg}. Incorporating Eq. 2 into Eq. 1, results in the Clausius-Clapeyron equation:

$$\frac{dP}{dT_s} = \frac{P}{R T_s^2} h_{fg}$$ (3)

which can be rearranged as:

$$\frac{1}{P} dP = \frac{h_{fg}}{R} \frac{dT_s}{T_s^2}$$ (4)

When Eq. 4. is applied to vapour from moisture in grain and to vapour from free water, the right hand side remains the same, thus the left hand sides of the two equations can be equated as:

$$\frac{1}{P_v} dP_v = \frac{h_{fg}}{h_{fg}^*} \frac{1}{P_{vs}} dP_{vs}$$ (5)

where:
P_v = actual pressure of water vapour (Pa),
P_{vs} = saturation pressure of water vapour (Pa),
h_{fg}^* = latent heat of vaporization of water in product (kJ/kg H₂O), and
h_{fg} = latent heat of vaporization of free water (kJ/kg H₂O).

Integration of Eq. 5 yields:

$$\ln P_v = \frac{h_{fg}}{h_{fg}^*} \ln P_{vs} + C$$ (6)

where C is a constant of integration. Thus plotting P_v and P_{vs} on logarithmic scales gives the ratio h_{fg}^*/h_{fg} as the slope of

the plotted line.

In this paper, the vapour pressure, P_v, at different temperatures was calculated as:

$$P_v = RH \ P_{vs}$$ (7)

where RH is the relative humidity as a fraction.

The values of the saturation vapour pressure, P_{vs}, at different temperatures were obtained from the saturation tables (ASHRAE 1989). The values of the RH in Eq. 7 were replaced by equilibrium relative humidities (ERH) obtained from the equilibrium moisture content (EMC) vs ERH relationships of Chung-Pfost for crops given in ASAE Standards (ASAE 1990):

$$ERH = \exp\left[\frac{-A}{T - C} \exp(-B \ EMC)\right]$$ (8)

where:
ERH = equilibrium relative humidity (fraction),
EMC = equilibrium moisture content (fraction db),
T = temperature (°C), and
A,B,C = coefficients taken from ASAE Standards (ASAE 1990).

The calculated values of P_v and P_{vs} at the same equilibrium moisture contents were then plotted on logarithmic scales. The slopes of the resulting straight lines were determined to give the ratio h_{fg}^*/h_{fg}. The following formula established by Gallaher (1951) was used to determine the dependence of the latent heat of vaporization of water from the product on its moisture content, M:

$$h_{fg}^* = h_{fg}[1 + a \exp(b \ M)]$$ (9)

The coefficients a and b were determined for barley, bean, corn, peanut kernel, rice, sorghum, soybean, durum wheat, hard and soft wheat, based on previously calculated ratios h_{fg}^*/h_{fg} (Eq. 6) at different vapour pressures which corresponded through ERH to different levels of equilibrium moisture contents.

Equilibrium moisture data for selected foods published by Iglesias and Chirife (1982) were used to estimate the latent heat of vaporization for these foods. Several mathematical equations have been used to describe water sorption isotherms of food materials. Since the best fit of mathematical formulas to experimental data was the only criterion in our calculations of the latent heat of vaporization, the following equations, as suggested by Iglesias and Chirife (1982), were used for estimating moisture contents at various temperatures and equilibrium relative humidities for these foods (Table 1).

Halsey's equation (Halsey 1948):

$$ERH = \exp\left[-\frac{B_2}{EMC^{B_1}}\right]$$ (10)

Henderson's equation (Henderson 1952):

$$1 - ERH = \exp[-B_2 \ EMC^{B_1}]$$ (11)

Oswin's equation (Oswin 1946):

Table I. Parameter B_1 and B_2 in Eqs. 10 to 12 for selected foods exposed to the adsorption process (Source: Iglesias and Chirife 1982)

Product	Temperature	Equation No.	B_1	B_2
Chamomile Tea	5°C	10	1.4204	21.2757
	25°C	10	1.4204	21.2757
	45°C	10	1.0367	6.1615
Celery	5°C	12	0.6203	12.6920
	25°C	12	0.6581	12.0212
	45°C	10	0.8800	4.4222
Cinnamon	5°C	11	2.3849	0.0013
	25°C	12	0.3426	10.7387
	45°C	12	0.4337	8.1014
	60°C	10	1.8015	22.9855
Cloves	5°C	12	0.3155	8.9129
	25°C	10	1.7926	25.6953
	45°C	10	1.4351	9.9545
Eggs	10°C	12	0.4805	8.0481
	37°C	12	0.5097	7.1133
	60°C	10	1.2875	6.4464
	80°C	12	0.5893	4.6593
Horse Radish	5°C	12	0.4823	13.8900
	25°C	12	0.5039	12.9501
	45°C	10	1.0340	6.3707
Starch Gel	-20-0°C	11	2.9305	0.0001
	10°C	11	2.3731	0.0009
	20°C	11	2.2011	0.0018
	40°C	11	2.4839	0.0015
	25°C	11	2.0178	0.0040
	35°C	11	1.8372	0.0069

$$EMC = B_2 \left[\frac{ERH}{1-ERH}\right]^{B_1} \qquad (12)$$

where equilibrium moisture content EMC in Eqs. 10 to 12 is expressed on a percent dry basis. Coefficients B_1 and B_2 are statistical parameters used for the description of the particular isotherm (Table I).

RESULTS AND DISCUSSION

The variation in latent heats of barley and three varieties of wheat are shown in Fig. 1. The symbols represent the values of $h_{fg}*/h_{fg}$ calculated from the equilibrium moisture content data (ASAE 1990) for selected moisture contents. The curves represent the best fit line computed based on Eq. 9. The coefficients a and b used in Eq. 9 are presented in Table II for different crops. Also, predicted results based on the coefficients given for wheat by Gallaher (1951) are incorporated in Fig. 1.

The $h_{fg}*/h_{fg}$ results for hard and soft wheat are very close, but there is a significant difference in the latent heat of vaporization between durum wheat and soft or hard wheat. For example, at a moisture content of 0.10 db the ratio $h_{fg}*/h_{fg}$ for durum wheat is 1.138 and for soft wheat it is 1.302, which is approximately 15% higher. Gallaher's prediction curve is closer to the predicted curves representing soft or hard wheat at low moisture contents (below 0.12 db) and it is closer to the curve for durum wheat above 0.14 moisture content db. This could be attributed to differences in the chemical composition between wheat cultivars (Lorenz and Kulp 1991). Starch and protein content play a significant role in water adsorption by kernels and the starch to protein content ratio varies depending on the cultivar. As wheat contains approximately 59 to 65% db starch, probably the differences in the latent heat of vaporization could be attributed to its starch content. Since the ASAE data (ASAE 1990) do not indicate chemical composition of the selected grains, it is difficult to analyze the latent heat of vaporization data from this stand point. In addition, environment has a
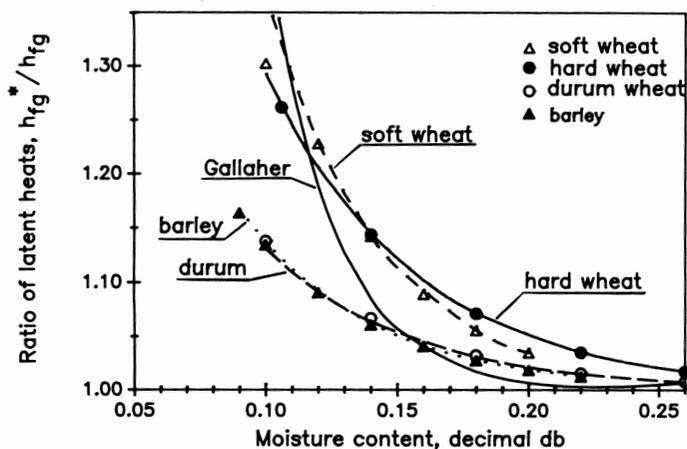
Fig. 1. Effect of moisture content on the latent heat of vaporization of different wheat cultivars and barley compared to Gallaher's (1951) model. Symbols indicate values of the ratios $h_{fg}*/h_{fg}$ calculated from the EMC-ERH characteristics at selected moisture contents. The curves indicate the predicted results based on Eq. (9) and the coefficients a and b determined in this work (Table II).
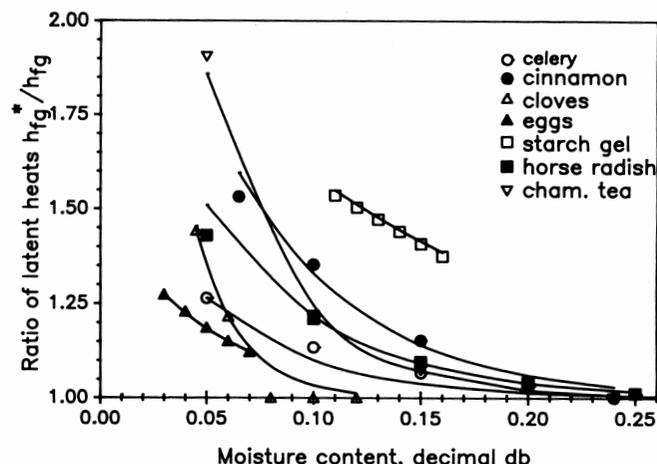

Fig. 2. Effect of moisture content on the latent heat of vaporization of main crops. Symbols indicate values of the ratios $h_{fg}*/h_{fg}$ calculated from the EMC-ERH characteristics at selected moisture contents. The curves indicate the predicted results based on Eq. 9 and the coefficients a and b determined in this work (Table II).

strong effect on the chemical composition and differences up to 3% db in starch and protein content for the same cultivar grown in different locations or different years are possible (Martens and Hlynka 1969). The variation of starch in barley is even greater. For the same barley types starch ranges from 21 to 64% db (Lorenz and Kulp 1991). In Fig. 1 the $h_{fg}*/h_{fg}$ ratio for barley is similar to the ratio for durum wheat which was probably due to the similar content of starch in these two different crops.

Figure 2 shows the effect of moisture content on the latent heat of vaporization in main crops. The curves represent the

predictions based on Eq. 9 using coefficients a and b, summarized in Table II. There is good agreement between the predicted and the calculated results based on the EMC curves. For moisture contents above 0.2 db, there is little difference between the heat of vaporization from the grain kernels and that of free water. Below that level of moisture, this difference increases significantly for such grains as corn and rice. Again, this could be attributed to starch content. Among the raw grains, corn has the highest starch content which is approximately 69% db (Lee et al. 1991). For the other grains, the ratio of heat of vaporization from the grains to that of free water increases at moisture contents below 0.12 db.

Table II. Derived coefficients a and b in Eq. 9 for some major crops

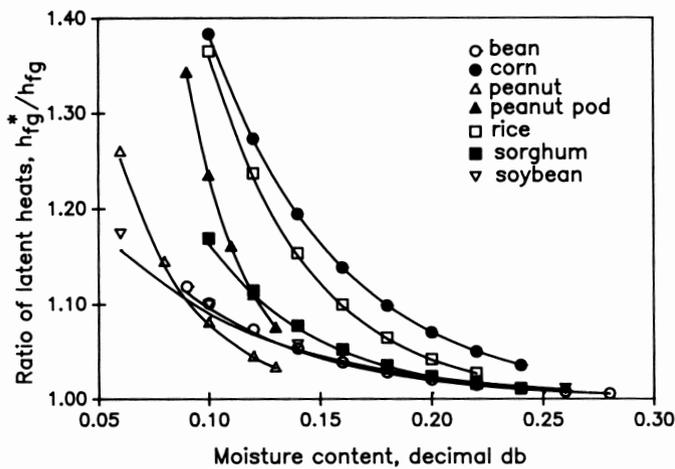| Crop	Coefficients		Range of moisture content (db)
	a	b	
Barley	1.0	-19.9	$0.09 \leq M \leq 0.22$
Bean	0.5	-16.0	$0.09 \leq M \leq 0.28$
Corn	2.1	-17.0	$0.10 \leq M \leq 0.24$
Peanut kernel	1.5	-29.2	$0.06 \leq M \leq 0.13$
Peanut pod	10.4	-37.9	$0.09 \leq M \leq 0.13$
Rice	3.2	-21.7	$0.10 \leq M \leq 0.14$
Sorghum	1.2	-19.6	$0.10 \leq M \leq 0.24$
Soybean	0.4	-13.9	$0.06 \leq M \leq 0.26$
Wheat, durum	0.8	-18.1	$0.10 \leq M \leq 0.26$
Wheat, hard	1.7	-17.6	$0.10 \leq M \leq 0.26$
Wheat, soft	3.9	-23.6	$0.10 \leq M \leq 0.20$
Wheat (Gallaher 1951)	23.0	-40.0	$0.10 \leq M \leq 0.18$

Fig. 3. Effect of moisture content on the latent heat of vaporization of selected foods. Symbols indicate values of the ratios $h_{fg}*/h_{fg}$ calculated from the EMC-ERH characteristics at selected moisture contents. The curves indicate the predicted results based on Eq. 9 and the coefficients a and b determined in this work (Table III).

The ratios of latent heat of vaporization of moisture from selected foods to that of free water are shown in Fig. 3. The data were obtained based on the EMC data and the appropriate formulas (Table I) published by Iglesias and Chirife (1982). The predicted results based on Eq. 9, with calculated coefficients a and b listed in Table III, are also shown in Fig. 3. It can be noticed that the latent heat of vaporization of free water is not significantly different than the latent heat of vaporization of water from products for moisture contents above 0.10 db for celery, cloves, and eggs; and for moisture contents above 0.15 db for chamomile tea and horse radish. For moisture contents below 0.10 db, the ratios $h_{fg}*/h_{fg}$ increase for all tested foods. The results for starch gel indicate significantly higher $h_{fg}*$ values than the h_{fg} of free water in the investigated range. The magnitude of its $h_{fg}*/h_{fg}$ ratio is the highest among tested crops and foods and is between 1.35 to 1.5 for moisture contents from 0.16 to 0.11 db, respectively. The predicted curve representing the ratio of $h_{fg}*/h_{fg}$ of cloves does not match exactly with the data. It may be possible that the experimental data of equilibrium moisture are not precise or the predicted curve cannot be represented by Eq. 9 for cloves.

Literature on water sorption in foods contains a substantial body of data covering a wide range of equilibrium moisture data for individual food materials (Iglesias and Chirife 1982). There is a large variation in the data for the same material from different laboratories even when the same methods were applied to the determination of water sorption isotherms. For instance, Spiess and Wolf (1983) compared the adsorption isotherms for beef measured by several researchers and found up to 10% db differences in the EMC values depending on the ERH range. Such a spread of results cast some doubts on the sorption data. Brooker et al. (1974) summarized the equilibrium moisture content values for cereal grains, oilseeds, and similar products from 22 sources. They concluded that variations in the values reported for one grain at the same temperature and humidity are common. The variation in the EMC data obviously influences the determination of the latent heat of vaporization if it is calculated using the method described in this paper.

The other problem with determining the equilibrium moisture content characteristics is that the sorption behaviour of a given material is influenced by any prior treatments it may have received. High or low drying temperatures may cause a change in sorption capacity. For example, Tuite and Foster (1963) reported that artificial drying lowers the equilibrium moisture content of corn by 0.5 to 1.0 percentage point as a result of slight chemical changes during the drying process which occur when kernels reach temperatures above 60°C. Chung et al. (1972) reported higher EMC values for broken corn kernels than for sound kernels and higher EMC values for sound harvested kernels than for heat-damaged kernels. An important implication of these observations is that differently treated kernels will influence the shape of the latent heat of vaporization curve.

CONCLUSIONS

It has been demonstrated that latent heat of vaporization of crops and foods can be predicted from moisture sorption isotherms. The model shows the same trends as suggested by Gallaher (1951). For moisture contents above 0.2 db, there is little difference between the heat of vaporization from the grain kernels, $h_{fg}*$, and that of free water, h_{fg}. Due to the variation in the moisture isotherm for any given product, there is considerable variation in the results of the heat of vaporization. A significant difference in the $h_{fg}*/h_{fg}$ ratios between durum wheat and soft or hard wheat was noticed.

Table III. Derived average coefficients a and b in Eq. 9 for some foodstuffs

Crop	Coefficients		Range of moisture content (db)
	a	b	
Chamomile Tea	3.0	-25.0	$0.05 \leq M \leq 0.24$
Celery	0.7	-19.5	$0.05 \leq M \leq 0.29$
Cinnamon	1.8	-17.0	$0.065 \leq M \leq 0.24$
Cloves	3.8	-47.7	$0.045 \leq M \leq 0.12$
Eggs	0.5	-20.0	$0.03 \leq M \leq 0.07$
Horse Radish	1.2	-17.1	$0.05 \leq M \leq 0.25$
Starch Gel	1.2	-7.1	$0.11 \leq M \leq 0.16$

The latent heat of vaporization of free water is not significantly different than the latent heat of vaporization of water from celery, cloves, and eggs above 0.10 mc db, and above moisture content of 0.15 db for chamomile tea and horse radish. The $h_{fg}*/h_{fg}$ ratio for starchy gel is 1.35 to 1.50 for the moisture range between 0.16 and 0.11 db, respectively. This is the highest ratio obtained for the tested crops and foods.

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