Determination of Physical and Thermal Properties of Herbal Compress Ball

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Abstract

This study investigated determination of physical and thermal properties of herbal compress ball. These properties are dispensable for studying heat transfer mechanism and process because herbal compress balls are generally heated by steam before use. Some physical and thermal properties of dried herbal compress ball were measured and characterized in this study. Some reliable measuring methods of such properties as well as in-house-made gas expansion pycnometer were developed. Experimental results showed that significant physical and thermal properties were successfully measured and in-house-built apparatus could work well with small error (±0.70%). Also, it was obvious that the temperature change in herbal compress ball was strongly affected by diffusion of steam inside the herbal compress ball and its thermal conductivity was close to that of woods.

Keywords: Herbal compress ball, physical properties, thermal properties, heat transfer

1. Introduction

Herbal compress ball (HCB) has been used in Thai culture since historical period. It composes of many kinds of herb such as phlai, turmeric, kaffir lime, lemongrass, tamarind's leaf, *Acacia Concinna's* leaf, borneol camphor, camphor, etc. [1], gathered in a piece of cloth wrapped like a small ball and used for medical purposes such as curing some diseases, relieving physical pains, muscle fatigue, etc. [2] Nowadays HCB has widely been exploited in beauty and spa business. Herbal compress balls have generally been produced in two types: dried and fresh ones. Fresh HCB is more beautiful, more aromatic and cheaper but it can be kept only 1-2 months in refrigerator. In contrast, dried HCB can be stored longer (12 months) without crucial degradation but its disadvantages are less attractive, less aromatic and more expensive. However, common HCBs sold in markets are dried type

Before use, a dried HCB is commonly sprayed with a small amount of water (to soften it), then heated for 10-15 minutes with steam by using a steam pot. The action of heating with steam causes cell wall to break and herbal substances called active ingredients are subsequently released to exterior. These active ingredients are important because they contain chemical substances that possess healing ability. Thus heat transfer process from steam to the HCB obviously plays an important role as a key factor that controls releasing rate of active ingredients, and consequently healing quality.

Literature review shows that researches related to HCB are somewhat available, but majority of them concern analyzing of active ingredients. Very rare information on heat transfer in which we are interested has been found. This present work is aimed on one hand to determine some physical and thermal properties of HCB which are dispensable for investigating heat transfer process during steaming, and on the other hand to develop reliable methods of measurement for some physical and thermal properties with in-house-made apparatus. These are steps to undergo prior to deal with heat transfer problems.

2. Materials

Herbal compress balls, as shown in Fig. 1, were purchased from Thai Medical College, Rajamangala University of Technology Thanyaburi and tested without further treatment. It composed of phlai, turmeric, zedoary, *Acorus Calamus,* wild turmeric, kaffir lime, lemongrass, tamarind's leaf, *Acacia Concinna's* leaf, borneol camphor, and camphor. HCB consists of two parts: bulb and handle. The herbal particles are in the bulb only.

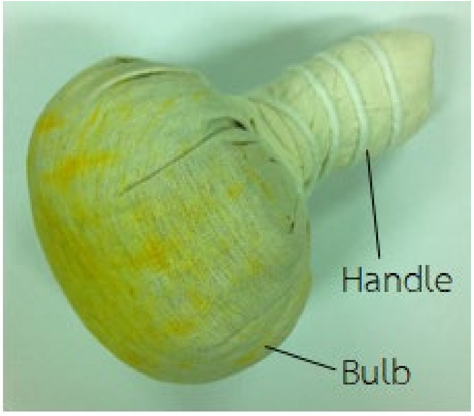

Fig.1 Herbal compress ball

3. Methods of measurement and apparatus

3.1 Mean diameter

Foods and grains have normally non-geometric shape. Therefore their sizes are usually reported in geometric mean diameter (*GMD*). Mohsenin [3] proposed to use 3 lengths measured in 3 different axes (length, width and thickness) in determining *GMD* of plants and animal materials. However, since HCB has a ball-like shape, it is better to represent the average diameter by using 4 diameters measured at 4 different angles (0, 45, 90 and 135° from horizontal line) as written in Eq. (*1*),

$$GMD = (ABCD)^{1/4} \qquad (1)$$

where *A, B, C* and *D* are diameters measured at 0, 45, 90 and 135° respectively. A Vernier caliper (Always) was used to measure all HCB's diameters.

3.2 Density and void fraction

Density of a material is defined as a ratio between its mass and volume occupied by that mass. To determine the density, one must know the volume of the object being measured. Since the HCB is made by wrapping small pieces of herbs with a cloth as a bulb, it contains void in its bulb and thus 2 types of density can be measured: true and bulk density. The bulk volume was obtained by using *GMD* with an assumption of spherical shape of the bulb. The true volume of solid was measured by using a method of gas displacement [4, 5, 6]. The device is called "gas expansion pycnometer". An in-house-built pycnometer, as shown in Fig. 2, composed of 2 cylindrical stainless-steel vessels of known volume, one was empty and the other contained HCB sample. They were connected with a ball valve at the lower part of the vessels. In the experiment the empty vessel was filled with dry compressed air to a pre-determined pressure while the other was at atmospheric pressure. After that the connection valve was open and the pressures in both vessels were allowed to equalize. The final pressure was recorded and the true volume of the sample was then determined by using Eq. (*2*),

Fig. 2 In-house-made gas expansion pycnometer

$$V_s = V_2 + V_1\left(1 - \frac{P_{1g}}{P_{fg}}\right) \quad (2)$$

Where

V_s was true volume of sample

V_1, V_2 were spatial volume of vessel 1 and 2 respectively

P_{1g} was gauge pressure of vessel 1 and

P_{fg} was final gauge pressure of both vessels.

A type K thermocouple and a pressure gauge were installed at vessel 1 to measure system temperature and pressure.

Eq. (*2*) was particularly derived for the case of which the sample was placed in a non-pressurized vessel. This equation was modified from the equation of Tamari [7] for which the sample was put in the pressurized vessel.

Once the true volume was determined, the true density (ρ) of HCB was then calculated by using Eq. (*3*).

$$\rho = \frac{M}{V_s} \quad (3)$$

For the bulk density (ρ_b), it was obtained by employing Eq. (*4*) [8]

$$\rho_b = \frac{M}{(\pi/6)(GMD)^3} \quad (4)$$

Once ρ and ρ_b were known, the void fraction of HCB could be determined by employing a relation shown in Eq. (*5*)

$$\varepsilon = 1 - \frac{V_s}{V_b} = 1 - \frac{\rho_b}{\rho} \quad (5)$$

3.3 Sphericity

Sphericity (ϕ_s) is a parameter that describes how similar to a sphere an object is. Therefore a sphere will have the sphericity of 1. Mohsenin [3] proposed relation between sphericity and GMD as shown in the following equation:

$$\phi_s = \frac{(ABC)^{1/3}}{A} \qquad (6)$$

Where *A, B* and *C* were length, width and thickness of material respectively. With little modification, we proposed an equation for determining of HCB to be:

$$\phi_s = \frac{GMD}{longest\ diameter} \qquad (7)$$

3.4 Moisture content

Dried HCB has some moisture content. In Thai community product standard 176/2553 [9], it must not be greater than 14% on wet basis. Many standard methods for moisture content determination are available. In this work AOAC 925.10 [10] was employed. Sample (HCB) was placed in an oven, in which the temperature was controlled at 120°C, for 2 hours. The moisture content (wet basis) was determined by the difference between the weight of sample before and after drying in the oven as written in Eq. (*8*).

$$MC = \frac{W_i - W_f}{W_i} \times 100\% \qquad (8)$$

3.5 Heat capacity

Heat capacity (c_p) is one of the most important thermal properties of a material. It explains how much heat must be applied to an object of a unit mass to raise its temperature by 1 degree. Several methods for determining c_p exist. One of the most convenient methods is "Differential Scanning Calorimetry" (DSC). In the present work, the Perkin Elmer, USA model DSC 8000 was used to determine c_p of HCB sample. The HCB had to be unwrapped and the herbal content was transferred into a cutting machine in which the herbal content would be reduced into small particles. The particles then were packed in a sample pan and placed in the DSC in order to perform c_p measurement with an empty pan as reference.

3.6 Thermal conductivity

Thermal conductivity (k) of a material is a property that indicates how fast a material can conduct heat across itself. Materials of high thermal conductivity have higher rate of heat transfer by conduction than those of low thermal conductivity. Direct measurement of HCB's thermal conductivity is difficult to perform because HCB is a mixture of several kinds of herb particles. In the present work, indirect method was attempted by wrapping the HCB with a plastic film and heating it in a steam pot. In this case no steam was allowed to diffuse into the bulb of the HCB, consequently heat was carried from the surface to the center of HCB by conduction alone.

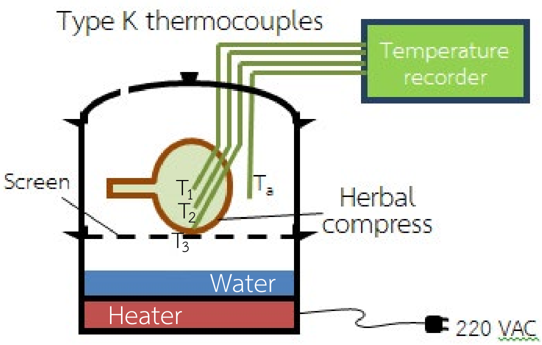

Fig. 3 Experimental setup

Fig. 3 shows the experimental setup. It composed of 2-chamber steam pot with a lid. Water was filled in the lower chamber to produce steam by using electric heater (220V. 1,300 Watts) and the HCB was placed on the screen located in the upper chamber. Four type K thermocouples were mounted through the lid, three of them were situated at the surface (under the cloth), at half the radius (R/2) and at the center of HCB. The last one was at the spatial room of the upper chamber to measure steam temperature. The four temperatures were recorded during steaming process until all temperatures were constant at their maximum values. The phenomena occurred in this system were the case of unsteady state conduction problem under conditions of negligible surface resistance ($Bi >> 0.1$). In this case and for one-dimensional heat flow, the solution for the temperature history has to follow Fourier equation [11],

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2} \qquad (9)$$

with the initial and boundary conditions

$T = T_0(x)$ at $t = 0$ for $0 \leqslant x \leqslant L$

$T = T_S$ at $x = 0$ for $t > 0$

and

$T = T_S$ at $x = L$ for $t > 0$

Where L is thickness/2. For the case in which the conducting object has a uniform initial temperature, solving of Eq. (9) gives the following solution

$$\frac{T - T_\infty}{T_0 - T_\infty} = \frac{4}{\pi}\sum_{n=1}^{\infty} \sin\left(\frac{n\pi}{L}x\right) e^{-(n\pi/2)^2 Fo} \qquad (10)$$

where n = 1, 3, 5...

The central history as well as at the surface and at midpoint of the plane wall, infinite cylinder, and sphere are presented in the form of Heissler charts as shown in Fig. 4 [11] allowing graphical method problem solving. The charts have four parameters, as shown in table 1: with unaccomplished change (Y) on the y-axis, the relative time (X) on the x-axis and the last two terms (n and m) as selectable parameters. For radial-direction heat transfer in a sphere, the characteristic length x becomes any radius r and x_1 is the radius R of the sphere.

To solve such kind of problem, it is necessary to know the convective heat transfer coefficient (h). Ainong [12] compared methods of determining heat transfer coefficients over moist food materials and proposed a following equation allowing prediction of h,

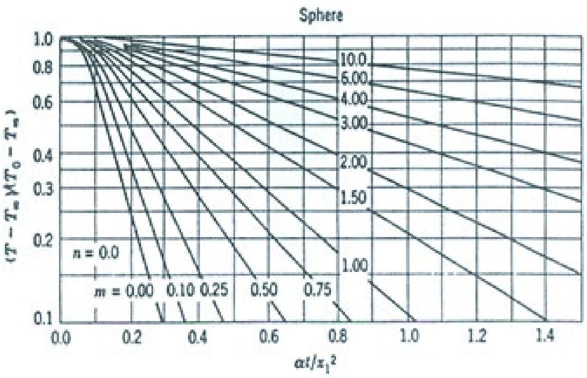

Fig. 4 Central temperature history of a sphere with initial uniform temperature [11]

Table 1 Symbols for unsteady-state chart

	Parameter symbol	Heat conduction
Unaccom-plished change, (a dimen-sionless ratio)	*Y*	$\frac{T_\infty - T}{T_\infty - T_0}$
Relative time	*X*	$\frac{\alpha t}{x_1^2}$
Relative position	*n*	$\frac{x}{x_1}$
Relative resistance	*m*	$\frac{k}{hx_1}$

$$h = 0.594\left[\frac{k_f^3 \rho_f^2 h_{fg}}{\mu_f}\right]^{0.25} \frac{1}{(T_a - T_s)^{0.70}} \quad (11)$$

where k_f was thermal conductivity of steam, ρ_f density, μ_f viscosity and h_{fg} latent heat of vaporization of steam respectively, T_a ambient (steam) temperature and T_s surface temperature. Eq. (*11*), obtained by Inverse Calculation Method, was originally developed for steam cooking of surimi paste, packed on an insulated stainless-steel tray, with uniform initial temperature of 12-14°C in a steam chamber using saturated steam at 100°C and 1 atm as the heating medium. One-dimensional heat conduction was assumed for heat transfer in surimi paste. Eq. (*11*) relates heat transfer coefficient (*h*) with thermal properties of the steam and the temperature difference between the ambient and the surface, no characteristic length appears in the equation. This provides simplicity in estimating heat transfer coefficient (*h*).

4. Results and Discussions

4.1 Mean diameter, sphericity, density and void fraction

The gas expansion pycnometer was first calibrated with a sample of known volume (a cube of wood of 7.70×7.85×7.60 mm). It was found that the volume determined by the pycnometer was 462.593 cm^3 while the true volume was 459.382 cm^3 which gave an error of ±0.70%.

Geometric mean diameter (*GMD*), true and bulk density, void fraction and sphericity of HCB tested in experiments are shown in table 2.

Table 2 Geometric mean diameter (*GMD*), true and bulk density, void fraction and sphericity of herbal compress ball

no.	*GMD* (mm)	ρ (kg/m^3)	ρ_b (kg/m^3)	ε	ϕ_s (-)
1	83.76	946.84	627	0.338	0.888
2	87.09	n.a.	n.a.	n.a.	0.897
3	87.67	n.a.	n.a.	n.a.	0.887
4	89.27	n.a.	n.a.	n.a.	0.881
5	87.45	n.a.	n.a.	n.a.	0.945

It was seen that the HCBs used were almost round, like a sphere. They had sphericity in the range of 0.881-0.945. The true and bulk density of sample no.1 had extendedly been determined. The results implied that HCB tested was moderately packed and sufficient room was provided for steam to diffuse through the HCB's bulb, helping for heat transfer rate to increase significantly.

4.2 Moisture content

The moisture content (wet basis) obtained after 2 hours of drying in an oven at 120°C (AOAC 925.10 method) was 6.78% which was within the standard value of 14%. Moreover, we had continued to further dry the HCB sample until nearly constant weight was attained and a result of 12.57% was obtained which was still in the limit of the standard value. The additional weight loss was probably due to loss of some volatiles remained in the sample.

4.3 Heat capacity

The experimental result of DSC for HCB sample was shown in Fig. 5.

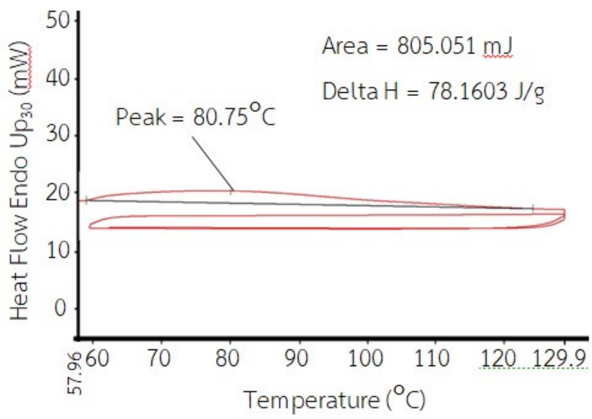

Fig. 5 DSC result: heat flow vs. temperature of HCB

It gave heat capacity of 1.1798 kJ/kg·°C for the scanning temperature range of 60-130°C.

4.4 Thermal conductivity

The change of 4 temperatures recorded during steaming process with wrapped HCB is shown in Fig. 6 and Fig. 7 shows the temperature change of bear HCB. As one could see, all temperatures increased from their initial temperatures to a maximum value which was close to steam temperature as time passed. The surface temperature started to rise first, then the temperature at R/2 and the central temperature was the last one. In both cases (wrapped and bear) the surface temperatures had already reached their maximum temperatures while the central temperatures still remained at their initial temperatures. At the end all temperatures stayed constant at their maximum values. The time needed for central temperature to reach its maximum value for bear HCB was 11 minutes, while for wrapped HCB it required 32 minutes. We could say that the heat transfer rate was nearly 3 times higher for bear HCB than that of wrapped HCB. It was certainly due to heat transfer by steam diffusion inside the bulb. Also it should be noted that some values of T_1, T_2 and T_3 were slightly higher than steam temperature (Ta); this was probably due to instrumental error.

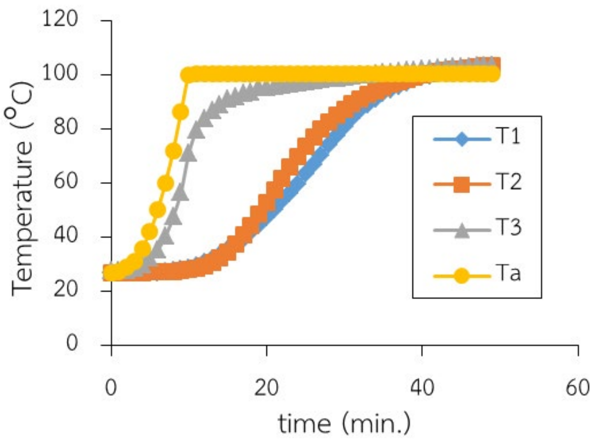

Fig. 6 Change of temperatures during steaming of wrapped HCB (T_a=steam, T_3=surface, T_2=R/2 and T_1=center) (d_p=0.0917 m, ρ_b= 493.67 kg/m^3, c_p=1179.8 J/kg·K)

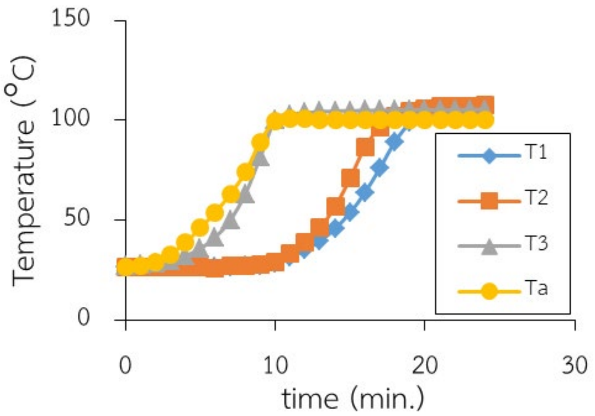

Fig. 7 Change of temperatures during steaming of bare HCB (T_a=steam, T_3=surface, T_2=R/2 and T_1=center) (d_p=0.0941 m)

To determine thermal conductivity (k) of HCB, the data for the case of wrapped HCB and the Heissler chart were used. To solve the problem, we needed to know heat transfer coefficient (h), from ambient steam to the HCB's surface, in the relative resistance parameter (m) and h could be calculated by using Eq. (*11*). Fig. 8 showed the values of h calculated and surface temperature (T_3) of HCB sample as a function of time. Consistently with Eq. (*11*) the values of h increased with increasing in surface temperature (T_3).

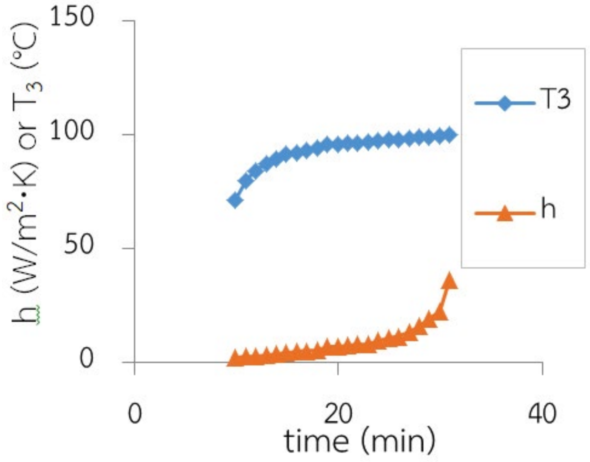

Fig. 8 h calculated and surface temperature (T_3) of HCB sample vs. time

By selecting the central point of the bulb, the relative position (*n*) became 0. The solving procedure was trial and error method with the following steps:

- Calculate *Y*.
- Assume *m*.
- For *n* = 0, read *X* which corresponded to the intersection between *Y* and *m* values.
- Knowing *X* then *k* could be calculated.
- Check whether *k* calculated gave the same *m* as assumed (if not the case, assume new value of *m* and redo solving).

In order to be able to calculate *h* by using Heissler chart and Eq. (*11*) we chose to investigate the value of central temperature between 10 to 31 minutes which were correspondent to the temperature range of 84-93°C for the reason that during this time the steam temperature (T_a) had already reached 100°C and stayed constantly at this value. The thermal conductivity (*k*) of

HCB obtained was 0.256-0.449 W/m·K in the temperature range selected (84-93°C). These values of k gave Bi in the range of 1.23 to 2.15 which satisfied the condition of negligible surface resistance ($Bi >> 0.1$).

5. Conclusions

The experimental results obtained can be drawn for the following conclusion:

1. Important physical and thermal properties of herbal compress ball were successfully determined in this work.

2. True volume of HCB can be reliably determined by a gas expansion pycnometer built in our laboratory.

3. Diffusion of steam plays an important role in increasing temperature of HCB during steaming, it makes increasing the heating rate to be 3 times faster.

4. The thermal conductivity (k) of HCB obtained in the range of 84-93°C is about 0.256-0.449 W/m·K which is close to that of woods (k~0.04-0.21 W/m·K, across grain) [13].

Though successful results, direct measurement method of k should be perform in the next step in order to validate the values above. Also, it will be very interesting to compare heat transfer phenomena with a mathematic simulation.

6. Acknowledgement

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Nomenclature

A, B, C, D	Diameter at 0, 45, 90 and 135° respectively or distance (m)
c_p	Heat capacity (kJ/kg·°C, J/kg·K)
d_p	Diameter of particle (m)
h	Convective heat transfer coefficient (W/m^2·K)
k	Thermal conductivity (W/m·K)
L	Thickness/2 (m)
M	Mass (kg)
MC	Moisture content (%)
P	Pressure (atm)
R	Radius (m)
t	Time (min)
T	Temperature (°C)
V	Volume (m^3)
W	Weight (kg)
x	Any radius or distance (m)
x_1	Radius of a sphere (m)
α	Thermal diffusivity = $k\rho/C_p$ (m^2/s)
ε	Void fraction (-)
ϕ_s	Sphericity (-)
ρ	Density (kg/m^3)

Dimensionless parameters

Bi	Biot number (hV/A)/k (-)
Fo	Fourier number ($\alpha t/(V/A)^2$) (-)

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1, 2	Vessel number 1 and 2 respectively
b	Bulk
f	Final or fluid
g	Gauge
i	Initial
s	Sample

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