Aerodynamic and some physical properties of sunflower seeds as affected by moisture content

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Abstract: The physical and aerodynamic characteristics of seeds can strongly influence their movements in the agricultural machine as well as in the air. The knowledge of the physical characteristics of particles is essential for the constructors and operators of agricultural machines. In this research some physical and aerodynamic properties of two Iranian edible seeds of sunflower cultivars (Badami and Doursefid) were studied in the moisture content range from 7% to 30% wet basis (w.b.). With decrease in moisture content the true density of Badami and Doursefid decreased from 561.02 to 457.29 kg/m^3 and 509.35 to 440.50 kg/m^3, respectively. For studying aerodynamic properties (terminal velocity and drag coefficient) the ratio of mass (g) to projected area (cm^2) of seeds were considered as K index. The terminal velocity of both seed decreased with decreasing K index and moisture content. The highest average terminal velocity was at moisture content of 30% for Badami and Doursefid as 7.08 and 6.97 m/s respectively, and the lowest was at the moisture content of 7% for both seed varieties, as 5.46 and 5.39 m/s respectively. With decrease in moisture content, drag coefficient tended to increase, so that its value for Badami and Doursefid changed from 0.59 to 0.95 and 0.52 to 0.75 respectively.

Keywords: sunflower seed, physical properties, aerodynamic properties

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1 Introduction

Sunflower (*Helianthus annuus L.*) seed is one of the most important oilseed crops due to its highly nutritious oil, and large quantity in a unit volume (Shukla et al., 1992). According to Iranian Bureau of Statistics (2005) over 35 varieties of sunflower seeds are cultivated in Iran quoted the production quantity in Iran (Khodabakhshian et al., 2009). The cultivation of sunflower seed in the country is aimed for oil production and fresh consumption with 90% and 10%, respectively (Khodabakhshian et al., 2009). Agricultural crops and food products have several unique characteristics that set them apart from engineering materials. Proper design of machines and processes to harvest, handle and store agricultural materials and convert these materials into food and feed require an understanding of their physical and aerodynamic properties (Naderiboldaji et al., 2008). The knowledge of the aerodynamic characteristics of grains (terminal velocity, drag coefficient) is significant for the construction and operation of machines, which treat substances with air flow and in all cases when substances are moved in the air (Polyak and Csizmazia, 2010). Some studies showed that the mass, volume, equivalent diameter, shape, projected area and moisture content of the agricultural product effect on aerodynamic properties (Uhl and Lamp, 1966; Haffar and Van Ea, 1990). Tabak and Wolf (1998), Bilanski and Lal (1965) reported that the condition and direction of collision of air has effect on aerodynamic properties of particles. Gorial and O’Callaghan (1990), Song and Lichfield (1991) and Zewdu (2007) studied the aerodynamic properties of different agricultural products. They considered factors of form and volume for calculating the aerodynamic properties of non-spherical and spherical particles and

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stated the drag coefficient as a function of Reynolds number. Sümer and Helvaci (2008) reported that when a particle moves in a fluid, its spherical shape influences on aerodynamic properties, as non-spherical particles have amount of fewer terminal velocity and greater drag coefficient. There are various researches on the aerodynamic properties of agricultural product and oil sunflower seeds, but there is fewer information on edible sunflower seeds, therefore in this study, the effect of some physical and aerodynamic properties on Iranian cultivars of edible sunflower seeds (Badami and Doursefid) at different moisture content were studied.

2 Background

A particle having projected area (A_p) and immersed in flowing fluid with velocity (V_f) and density (ρ_f) is subjected to a drag force (F_d) given by (Menzies and Bilanski, 1968):

$$F_d = C_d A_p \frac{\rho_f V_f^2}{2} \tag{1}$$

When a particle falls freely through air or during the separation of foreign material from grain the fundamental forces involved are the weight of the particle and the aerodynamic drag (Sümer and Helvaci, 2008). In free fall, stable velocity of particle depends on its physical properties and density of air. A particle of mass (m_P) in a free fall obtains a constant terminal or suspension or critical velocity (V_t) at which the net gravitational force (F_g) equals the resisting upward aerodynamic drag force (F_d). When terminal velocity is attained under steady-state conditions, the particle motion will be upward or downward, depending on whether the particle density (ρ_P) is smaller or greater than that of the fluid, respectively. Therefore, knowledge of the terminal velocities of particles defines the range of fluid velocities affecting the effective separation of the particles in the fluid stream. Consequently, terminal velocity is an important aerodynamic characteristic in pneumatic separation of particles (Mohsenin, 1986; Edwin et al., 2003).

When the fluid velocity (V_f) is equal to terminal velocity of the particle (V_t), drag coefficient can be obtained in terms of the terminal velocity, as:

$$F_g = F_d \tag{2}$$

$$m_P g\left[\frac{\rho_P - \rho_f}{\rho_P}\right] = \frac{C_d A_P \rho_f V_t^2}{2} \tag{3}$$

$$V_t = \left[\frac{2m_P g(\rho_P - \rho_f)}{\rho_P \rho_f C_d A_P}\right]^{\frac{1}{2}} \tag{4}$$

$$C_d = \frac{2m_P g(\rho_P - \rho_f)}{A_P \rho_P \rho_f V_t^2} \tag{5}$$

For the spherical bodies with an effective dimension (D_P), the product projected area and weight can be given by (Mohsenin, 1986):

$$A_p = \frac{\pi d_P^2}{4} \tag{6}$$

$$W = \frac{\pi g \rho_f d_P^2}{6} \tag{7}$$

Mohsenin (1986) stated both drag coefficient and Reynolds number (Equation (8)) include a velocity term, calculation of terminal velocity from Reynolds number and drag coefficient relationship require a trial-and-error solution.

$$N_R = \frac{V_t D_P \rho_f}{\mu} \tag{8}$$

Combining Equations (4)-(8), the drag coefficient can be given by

$$C_d N_R^2 = \frac{4g\rho_f d_P^3(\rho_P - \rho_f)}{3\mu^2} \tag{9}$$

To eliminate a trial-and-error solution, the terms $C_d N_R^2$ (Equation (9)) are first calculated and plotted against N_R. Mohsenin (1986) reported that drag coefficient for spherical particles in the air, when Reynolds number is variable from 1.0×10^3 to 2.5×10^5, can be assumed constant and it is about 0.44 for the spherical particles that are immersed into fluid. Because most of agricultural products have irregular shapes, various definitions for consideration as spherical equivalent diameter are expressed. Mohsenin (1986) and Jain and Bal (1997) stated the following relations for equivalent diameter and spherical that are defined as

$$\phi = \frac{(abc)^{1/3}}{a} \tag{10}$$

$$D_P = \left(a\frac{(b+c)^2}{4}\right)^{1/3} \tag{11}$$

The theory of the aerodynamic characteristics of regularly shaped bodies is well elaborated; however, seed grains are irregularly shaped. Therefore, in this research the characteristics of irregularly shaped grains (sunflower seeds) were studied.

3 Materials and methods

3.1 Sample preparation

The Iranian sunflower seeds used in this study shown in Figure 1, consisted of Badami and Doursefid varieties which were obtained from the Experimental Orchard of University of Tabriz at the time of harvesting season. The initial moisture content of seeds was determined by oven drying at 105 ± 2°C for 24 h (ASAE, 1998). To obtain the different moisture contents of the products used in this study, an air conditioning unit equipped with devices for controlling the temperature and relative humidity of the drying air were used to accomplish the drying process (AfonsoJunior et al., 2007). In this research samples were prepared at four moisture levels of 30%, 20%, 15% and 7% (w.b.) which are the moisture contents from harvesting to processing.

a. Badami b. Doursefid

Figure 1 Edible sunflower seed of Badami and Doursefid

3.2 Physical properties

Dimension and mass of seeds were measured by a digital caliper with an accuracy of 0.01 mm and a digital scale with 0.01 g respectively (Jafari, 2008). The sphericity of seeds was calculated using Equation (10). Projected area was obtained according to method of Gupta et al. (2007) and Equation (12). True density is defined as the ratio of mass of the sample to its true volume (Mohsenin, 1986) as obtained by:

$$A_p = \left(\frac{\pi}{4}\right)ab \quad (12)$$

$$\rho_T = \frac{m_P}{V_T} \quad (13)$$

3.3 Aerodynamic properties

For measuring the terminal velocity, vertical wind tunnel according to recommendation of Mehta (1977) and Afonso Junior et al. (2007) was built and evaluated. In this device the fan was powered by a three-phase 3 hp electrical motor and rate of air flow was controlled by diaphragm adapted to the entrance inlet of air or alteration of rotational speed of motor with inverter of TECO model as shown in Figure 2. Before measuring the terminal velocity, the mass of single seed by digital scale with accuracy of 0.01 g and projected area using Equation (12) was determined and then was placed in the test section of wind tunnel. A circular duct made of Plexiglas was used to observe particles while suspended. A seed cleaner was modified and adopted in order to measure particles suspension velocities. Air velocity was increased gradually till the particle was suspended. At a point just above the suspension point, provision was made to allow the digital hot wire anemometer into the duct to measure the speed of the air. The anemometer measured to resolution of 0.1 m/s. For each level of moistened sample, 10 replicates of terminal velocity measurements were taken and the average reported and the drag coefficients were calculated using Equation (5) (Zewdu, 2007). The mass and projected area seeds are effective factors on aerodynamic properties. Sunflower seeds have various mass and projected area, therefore in this research, the ratio of mass to projected area of seeds was assumed as *K* index (g/cm^2) to study its variation on properties. The data were subjected to regression analysis for fitting the experimental data to models that predict the terminal velocity or drag coefficient as a function of the moisture content and *K* index. For adjusting the models to experimental data, the STATISTICA version 7.0 computational programme was used.

Figure 2 Vertical wind tunnel used to determine the terminal velocity of seeds

4 Results and discussion

The mean and standard deviation of the true density, sphericity, projected area and equivalent diameter of the Badami and Doursefid for different moisture content are shown in Tables 1 and 2 respectively. The results show with reduction of moisture content from 30% to 7% (w.b.), true density, sphericity, projected area and equivalent diameter decrease for both cultivars. These results are in accordance with results of Afonso Juniorb et al. (2007) for the coffee and Jafari (2008) for the sunflower seeds. Figure 3 show that the value of equivalent diameter of Badami and Doursefid changed from 11.90 to 11.17 and 11.57 to 10.78 mm at moisture content from 30% to 7% respectively. The relationship between equivalent diameter of seeds and moisture content represented as follows:

$$D_p \text{ (Badami)} = 3.219M_c + 10.86 \quad (R^2 = 0.93)$$

$$D_p \text{ (Doursefid)} = 3.467M_c + 10.47 \quad (R^2 = 0.96)$$

Table 1 Average values (Mean) and standard deviation (SD) for true density, sphericity, projected area and equivalent diameter of the Badami for different moisture contents

Moisture contents (MC)/% w.b.	True density (ρ_t)/kg m^{-3}		Sphericity (ϕ)/%		Projected area (A_p)/cm^2		Equivalent diameter (D)/mm	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
30	561.02	8.99	43.54	5.02	1.97	0.44	11.90	1.45
20	507.15	5.53	42.12	4.88	1.79	0.41	11.43	1.42
15	481.97	4.66	41.66	4.84	1.76	0.40	11.28	1.41
7	457.29	7.12	41.41	4.84	1.69	0.40	11.17	1.40

Table 2 Average values (Mean) and standard deviation (SD) for true density, sphericity, projected area and equivalent diameter of the Doursefid for different moisture contents

Moisture contents (MC)/% w.b.	True density (ρ_t)/kg m^{-3}		Sphericity (ϕ)/%		Projected area (A_p)/cm^2		Equivalent diameter (D)/mm	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
30	509.35	10.91	61.89	6.16	1.71	0.34	11.57	1.45
20	461.02	17.78	59.46	6.40	1.64	0.33	11.10	1.43
15	451.19	5.99	58.58	6.60	1.56	0.34	10.94	1.45
7	440.55	12.76	58.58	6.56	1.54	0.33	10.78	1.46

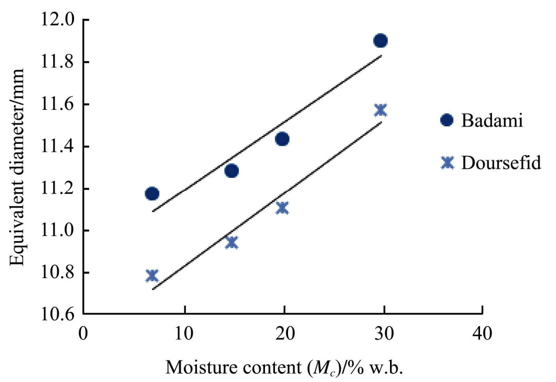


Figure 3 Plot of equivalent diameter (D_p) against moisture content (M_c)

The experimental results for the true density with respect to moisture content are shown in Figure 4. The values of true density for Badami and Doursefid were found to decrease significantly from 561.02 to 457.29 and 509.35 to 440.55 kg/m^3 in the moisture range of 30% to 7% (w.b.) respectively. The trend observed in this study was in agreement with the studies made for wheat seeds (Nalbandi, 2008). The true density for seeds has the following relationships with its moisture content:

$$\rho_t \text{ (Badami)} = 457M_c + 419.6 \quad (R^2 = 0.98)$$

ρ_t (Doursefid) = $300.3M_c + 411.5$ ($R^2 = 0.90$)

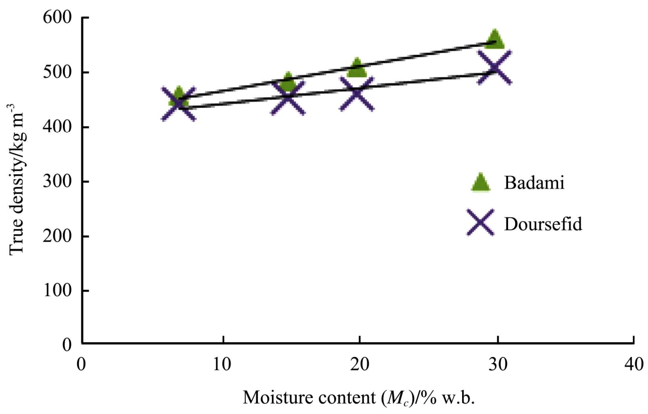


Figure 4 Plot of bulk density (ρ_t) against moisture content (M_c)

The mean and standard deviation value of K, terminal velocity and drag coefficient of the Badami and Doursefid for different moisture content are shown in Tables 3 and 4 respectively. Results show that with a decrease in moisture content from 30% to 7%, there was a reduction in the value of K index. A similar behaviour was observed in the results of Song and Litchfield (1991), who studied the aerodynamic properties of several types of agricultural products using the same methodology. It has been shown when the moisture content decreased, terminal velocity for Badami and Doursefid changed from 7.074 to 5.46 m/s and 6.90 to 5.417 m/s respectively and it means that terminal velocity tended to decrease, and the values for Badami were more than for Doursefid. Also drag coefficient for Badami and Doursefid changed from 0.59 to 0.951 and 0.517 to 0.751 respectively. Similar results were found by Gupta et al. (2007), Khodabakhshian et al. (2009) for sunflower seeds and Afonso Junior et al. (2007) who used the same methodology for coffee cherry and beans. For an improved evaluation of the aerodynamic properties of the seeds some regression equations were modified to predict average terminal velocity and drag coefficient as a function of moisture content and K index. The correlations are presented in Table 5 and the respective relationships are presented in Figures 5 and 6. A decrease in terminal velocity value with decrease in moisture content and K index was observed as shown in Figures 5 and 6. This relationship confirms the view that with a decrease in moisture content, value of K index for seeds decreased and it caused to decrease in terminal velocity and increase in drag coefficient. Values of the drag coefficient for the Doursefid seeds were slightly lower than Badami seeds (Tables 3 and 4). This might be associated with the more spherical form of the Doursefid seeds compared to the Badami seeds.

Table 3 Average values (Mean) and standard deviation (SD) for K index, terminal velocity, drag coefficient of the Badami

Moisture contents (MC) /% w.b.	Ratio of mass to projected area (K) /g cm^{-2}		Terminal velocity (V_t) /m s^{-1}		Drag coefficient (C_d)	
	Mean	SD	Mean	SD	Mean	SD
30	19.60	0.035	7.074	0.62	0.590	0.12
20	19.30	0.038	6.279	0.63	0.473	0.10
15	19.03	0.042	5.632	0.42	0.743	0.18
7	18.42	0.032	5.460	0.53	0.951	0.14

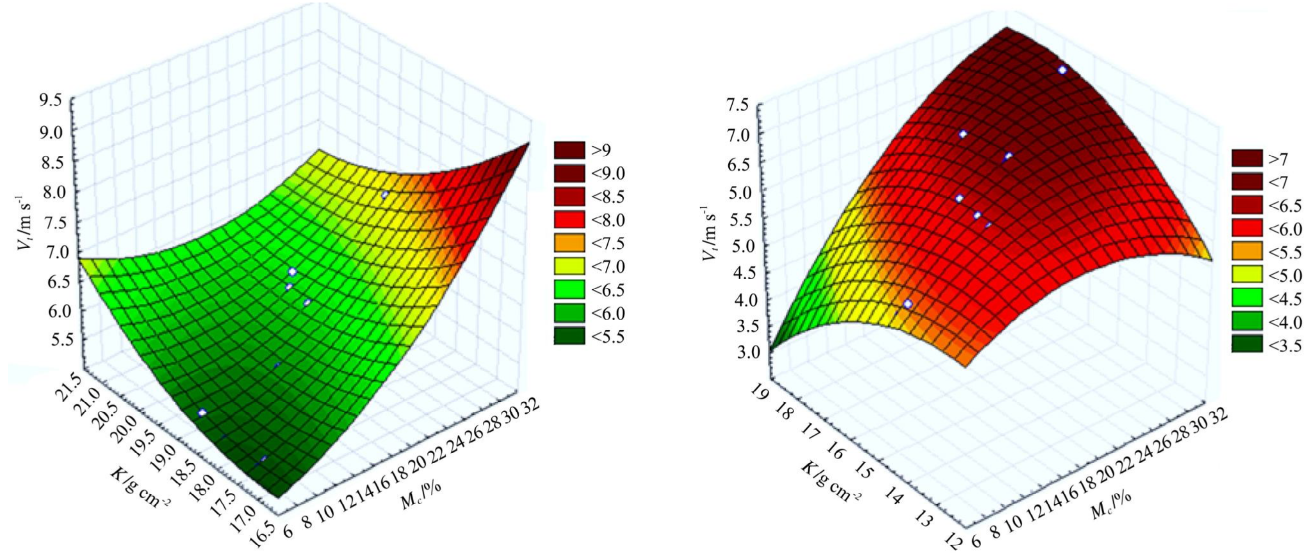
Table 4 Average values (Mean) and standard deviation (SD) for K index, terminal velocity, drag coefficient of the Doursefid

Moisture contents (MC) /% w.b.	Ratio of mass to projected area (K) /g cm^{-2}		Terminal velocity (V_t) /m s^{-1}		Drag coefficient (C_d)	
	Mean	SD	Mean	SD	Mean	SD
30	16.06	0.036	6.9	0.702	0.517	0.087
20	15.51	0.023	6.58	0.44	0.533	0.07
15	14.31	0.025	6.313	0.485	0.551	0.067
7	14.28	0.025	5.417	0.449	0.751	0.132

Table 5 Adjusted regression equation for predicting the terminal velocity V_t and the drag coefficient C_d of cultivars of sunflower seeds of the Badami and Doursefid, as a function of the moisture content MC and ratio of mass to projected area K index, with the respective determination coefficients R^2

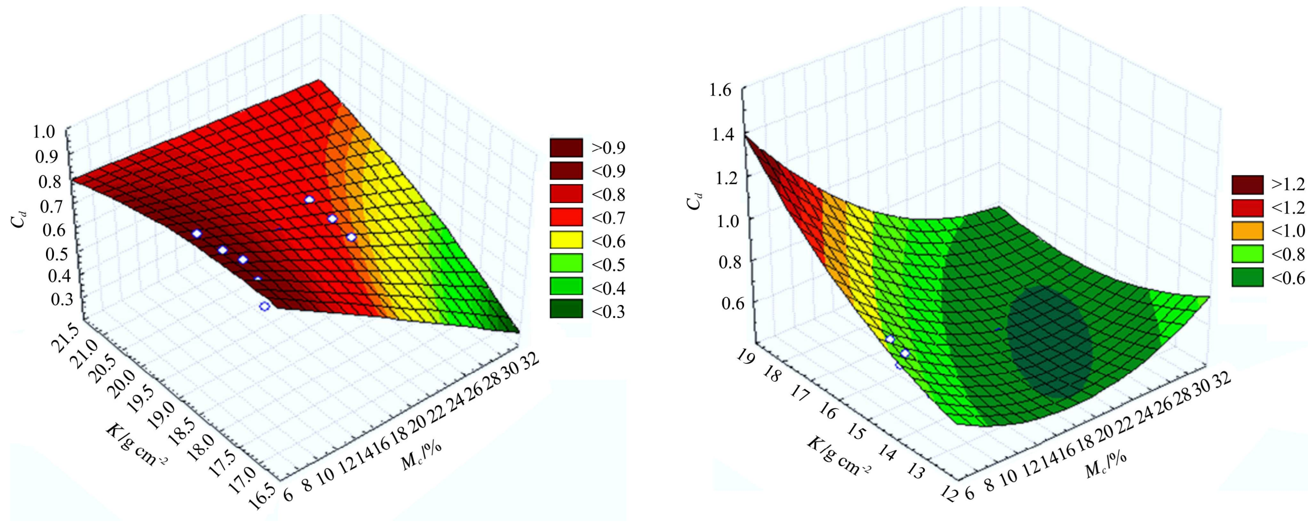
Cultivar seed	Parameter	Regression equation
Badami	Terminal velocity	$V_t = 23.6941+0.4986x-2.3778y+0.0035x^2-0.0292xy+0.0757y^2$ R^2=94%
	Drag coefficient	$C_d = -0.6528-0.1009x+0.2301y-2.5159\times10^{-5}x^2+0.0046xy-0.0075y^2$ R^2=93%
Doursefid	Terminal velocity	$V_t = -2.0567-0.1237x+1.2053y-0.0045x^2+0.0237xy-0.0543y^2$ R^2=90%
	Drag coefficient	$C_d = 1.4735+0.0156x-0.1633y+0.0012x^2-0.0048xy+0.0095y^2$ R^2=83%

Note: x, y indicate the moisture content and K index respectively.



a. Badami b. Doursefid

Figure 5 Values of terminal velocity at the moisture content and the ratio of mass to projected area *K* of the product



a. Badami b. Doursefid

Figure 6 Values of drag coefficient at the moisture content and the ratio of mass to projected area *K* of the product

5 Conclusions

Considering the sunflower seeds as spherical products, the decrease in moisture content and the ratio of mass to projected area, *K* index affected the aerodynamic properties of seeds and decreased in terminal velocity while drag coefficient increased for both the studied cultivars.

Average of true density, sphericity, projected area and equivalent diameter for Badami and Doursefid reduced with decreasing moisture content from 30% to 7% (w.b.). The values of true density for Badami and Doursefid were found to decrease significantly from 561.02 to 457.29 and 509.35 to 440.55 kg/m^3 in the moisture range of 30% to 7% (w.b.) respectively.

With decreasing in moisture content from 30% to 7% (w.b.), terminal velocity for Badami and Doursefid reduced from 7.074 to 5.46 and 6.90 to 5.417 m/s respectively, and drag coefficient increased from 0.59 to 0.951 and 0.517 to 0.751 respectively.

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Notation

a, *b*, *c*	Length, width, thickness , mm
A_p	projected area of the particle normal to the direction of the motion, m^2
C_d	drag coefficient, dimensionless

D_P	equivalent spherical diameter, m
F_d	drag force, N
F_g	gravitational force, N
g	gravitational acceleration, m/s^2
K	The ratio of mass to projected area, g/cm^2
m_P	mass of the particle, kg
N_R	Reynolds number, dimensionless
V_t	Terminal velocity, m/s
V_f	Velocity of fluid or gas, m/s
ρ_p	density of particle, kg/m^3
w	weight of the particle, kg
ϕ	Sphericity, dimensionless
μ	absolute viscosity of fluid, kg/ms
P_t	True density, kg/m^3
V_T	True volume of particle, m^3
ρ_f	density of fluid, kg/m^3
M_c	Moisture content, % w.b.

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