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EFFECT OF TEMPERATURE AND PRESSURE ON MOISTURE DIFFUSION CHARACTERISTICS OF PADDY (Cv. MTU 1075)

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Abstract: Parboiling is an important and energy intensive unit operation in rice processing. Proper management of parboiling can reduce the energy requirement during parboiling and the associated cost. Soaking and steaming are the two major steps in parboiling. Soaking of paddy is usually carried out under atmospheric pressure, which takes more time. The temperature of soak water affects the rate of moisture adsorption and diffusion. The pressure during soaking and steaming also affects the process and consequently, affects the overall economics of parboiling. The hydration characteristic of paddy (Cv. MTU 1075) was studied at different conditions with the basic objective to standardize parameters for these unit operations. Soaking was carried out at four levels of soaking temperature under atmospheric pressure. Similarly hydrostatic soaking at pressure levels of 2.0, 4.0 and 6.0 $kg\cdot cm^{-2}$ was studied at a constant soak water temperature of 70°C. Steaming was carried out at 0.5, 1.0, 1.5, 2.0 and 2.5 $kg\cdot cm^{-2}$ pressure levels. The initial moisture content of paddy was varied at three levels. It was observed that the soaking temperature and pressure and steaming pressure affected the rate of moisture absorption by the grain and thus the time requirement. The diffusion coefficient was independent of initial moisture content and showed Arrhenius type relationship with temperature of soaking and steaming. The diffusion coefficient of paddy ranged between 8.939×10^{-5} to 2.678×10^{-4} $cm^2\cdot min^{-1}$ for steaming under pressure, 7.01×10^{-6} to 1.399×10^{-5} $cm^2\cdot min^{-1}$ for hydrostatic pressure soaking at 70°C and 1.898×10^{-6} to 1.11×10^{-5} $cm^2\cdot min^{-1}$ for soaking under atmospheric pressure at different temperature. The diffusion constant was calculated as 0.01345 $m^2\cdot min^{-1}$ and activation energy for moisture diffusion was 35.19 $kJ\cdot g\text{-}mol^{-1}$.

Key words: *parboiling, hydrostatic soaking, steaming, diffusion coefficient*

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INTRODUCTION

Rice is the staple food of India and more than 50% of the rice produced is consumed in the country in parboiled form. Rice is parboiled in many countries of South East Asia and in some developing countries in South Africa. Parboiling increases milling yield, storage stability and nutritional value of rice and changes the taste of cooked rice which is liked by many classes of people [1]. Conventional parboiling method involves three steps, viz. soaking, steaming and drying. All these unit operations consume huge amount of energy. Hence, the development of new energy efficient processes and improvement in the existing processing operation for parboiling has been major field of research. Some studies have been conducted in the past to modify the conventional paddy parboiling methods in view of energy conservation and initial investment [2, 3]. Some attempts were also made even to eliminate the steaming process in parboiling, which could help in avoiding the high investment due to the installation of a boiler [2, 4-7]. However, to affect proper gelatinization, proper absorption and distribution of moisture in the grain along with infusion of heat energy are quite important. Some studies have been conducted on the hydration characteristics of paddy to present the moisture absorption behaviour of rice during soaking and steaming, which ultimately facilitates the design of the parboiling process [8-10]. However, the process and parameters may vary for different varieties of paddy. Even for a single variety of paddy the physical and other engineering properties change with the moisture content [11]. Therefore, there is a need to study the rate of moisture absorption and diffusion by the grain at different process conditions to standardize different parameters for processing, and hence, the moisture absorption characteristics of a popular and widely cultivated variety of paddy (Cv. MTU 1075, local name: *Pushyami* also known as *IET 18482*) was studied under different soaking temperature and pressure, and steaming pressure at different initial moisture levels.

MATERIALS AND METHODS

Freshly harvested paddy was shade dried and the moisture content was determined just before the start of the experiment. Three initial moisture contents in the range of 13-30 g per 100 g dry matter were taken for the study. The temperature of soak water was maintained at 40°, 50°, 60° and 70°C. The soaking experiment was carried out in a hot water bath maintained at ±2°C. The moisture content of paddy was measured at different time in hot air oven to determine the rate of moisture absorption. The moisture gain during hydrostatic soaking of paddy was studied at 2.0, 4.0 and 6.0 $kg \cdot cm^{-2}$ absolute pressure in a hydrostatic pressure vessel. During soaking of paddy under pressure, the temperature of soak water was kept constant at 70°C. The soaking experiment was continued for up to 6 hours.

The moisture absorption during steaming was studied by employing five levels of steam pressure, viz. 0.5, 1.0, 1.5, 2.0 and 2.5 $kg \cdot cm^{-2}$. The pressure vessel was suitably modified for the purpose. The observations were taken up to 25 minutes.

The rate of moisture absorption during the above experiment was analyzed to find out the values of diffusion coefficient, diffusion constant and the activation energy for moisture diffusion.

Diffusion coefficient. The moisture movement in paddy grain during soaking and steaming is governed by the basic principle of moisture diffusion. Analytical expressions predicting moisture movement in a grain based on diffusion theory have been used by [3] with suitable assumptions. Application of these equations requires knowledge of two parameters, diffusion coefficient and saturation moisture content for different hydrating conditions.

It was assumed that the surface layers of the grain attained equilibrium with the medium and reached the saturation moisture content immediately after exposure to the hydrating medium. Diffusion of moisture from the surface layers into the grain took place due to moisture concentration gradient between the adjacent layers in the kernel, as governed by Fick's law.

The form of equation obtained was [3]:

$$\frac{\partial C}{\partial t} = -\phi\left(\frac{\partial q}{\partial r} + \frac{2}{r}q\right) \quad (1)$$

where:

ϕ [-] - shape factor of paddy,

C [g·cc^{-1}] - moisture concentration at any characteristic radius 'r' and time,

t [sec] - time,

q [g·cm^{-2}·min^{-1}] - rate of mass transfer per unit area of cross section,

r [cm] - characteristic radius within the paddy grain.

For grain, ϕ is given by:

$$\phi = \frac{s}{v} x \frac{a}{3} \quad (2)$$

where:

s [cm^2] - surface area of paddy grain,

υ [cm^3] - volume, for the paddy grain,

a [cm] - characteristic dimension of paddy grain (half of the breadth of paddy grain)

As per Fick's law:

$$q = -D\frac{\partial C}{\partial r} \quad (3)$$

where:

D [cm^2·min^{-1}] - diffusion coefficient.

Substituting the values:

$$\phi D\left(\frac{\partial^2 C}{\partial r^2} + \frac{2}{r}\frac{\partial C}{\partial r}\right) = \frac{\partial C}{\partial t} \quad (4)$$

The equation is similar to diffusion equation for a sphere under similar conditions and is the basic equation governing the moisture movement in a paddy grain at any characteristic radius *r* and time of increment *t*.

Eq. (4) was solved initially for constant values of diffusion coefficient and saturation moisture content and then the solution was modified for varying values of diffusion coefficient and saturation moisture content and then the solution of the above equation with suitable initial and boundary conditions, and further simplification yielded the following equations [8]:

$$\frac{M_t - M_0}{M_s - M_0} = \Psi(t) \quad (5)$$

where $\Psi_{(t)}$ is the infinite series defined as:

$$\psi(t) = 1 - \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp(-n^2 \pi^2 \phi Dt / a^2) \tag{6}$$

where:

$\Psi_{(t)}$ [-] - infinite series to find out moisture ratio,
M_0 [-] - moisture content at the beginning (at time $t = 0$),
M_t [-] - moisture content at any time, t,
M_s [-] - saturation moisture content.

The use of Eq. (5) for determination of D from the moisture ratio at any time requires summation of infinite series to the point of convergence. An empirical relationship was developed to estimate the value of the series as follows.

$$\psi(t) = -0.028\, d + 1.029\, d^{\,0.54} - 0.0221 \tag{7}$$

In this equation d is a dimensionless variable, which is defined as:

$$d = \frac{\pi^2 \phi Dt}{a^2} \tag{8}$$

where:

d [-] - dimensionless variable,
D [$cm^2 \cdot min^{-1}$] - diffusion coefficient,
a [cm] - half the breadth of paddy grain (characteristic outer radius of paddy grain).

Thus, from the moisture ratios the value of diffusion coefficient was obtained.

Saturation moisture content. The principle used in the method is that for constant values of saturation moisture content M_S and diffusion coefficient D, the moisture gain $(Mt - Mo)$ by a grain at any time is directly proportional to the moisture driving potential $(Ms - Mo)$.

$$(M_t - M_0) \propto (M_S - M_0) \tag{9}$$

or

$$(M_t - M_0) = k \cdot (M_S - M_0) \tag{10}$$

$$(M_t - M_0) = - k \cdot Mo + \delta, \text{ where } \delta = k \cdot Ms \tag{11}$$

The diffusion coefficient was correlated to treatment temperature by Arrhenius type of relationship.

$$D = D_0 e^{E_a / RT} \tag{12}$$

where:

E_a [cal/g-mole] - activation energy,
R [-] - gas constant,
T [K] - temperature of treatment.

RESULTS AND DISCUSSION

The MTU 1075 is a slender variety of paddy. The average length, breadth and thickness of the samples were found out to be 5.74±0.084 cm, 2.1±0.224 cm and 1.84±0.089 cm. The length breadth ratio was observed to be 3.132±0.161.

Hydration characteristics of paddy during hot water soaking. Fig. 1 shows the moisture gain of paddy for different durations of soaking at different temperatures and initial moisture contents. It was observed that the rate of moisture gain reduced with time as expected. At any given temperature and duration of soaking, the rate of moisture gain was higher with lower initial moisture content than that with higher moisture content. This was due to the fact that rate of moisture diffusion into the grain was directly proportional to the difference between saturation moisture content and initial moisture content, i.e. the moisture driving potential. Higher the soaking temperature higher was the rate of moisture absorption by the grain. The rate of moisture diffusion was higher initially up to about 60 min after which it decreased. At low initial moisture content variation in temperature from 40°C to 50°C caused increase in the moisture diffusion. However, no such difference was observed for higher moisture contents.

Hydration characteristics of paddy during pressure soaking. Fig. 2 shows the rate of moisture gain with respect to time for the paddy for three different pressures. The rate of moisture absorption decreased with time and the plots indicate logarithmic moisture migration. It was also observed that the rate of moisture migration was higher with lower initial moisture contents than that with higher initial moisture contents. Higher pressures resulted in higher moisture gain by the grain, but this increase in the rate of moisture migration was not noteworthy at higher pressures.

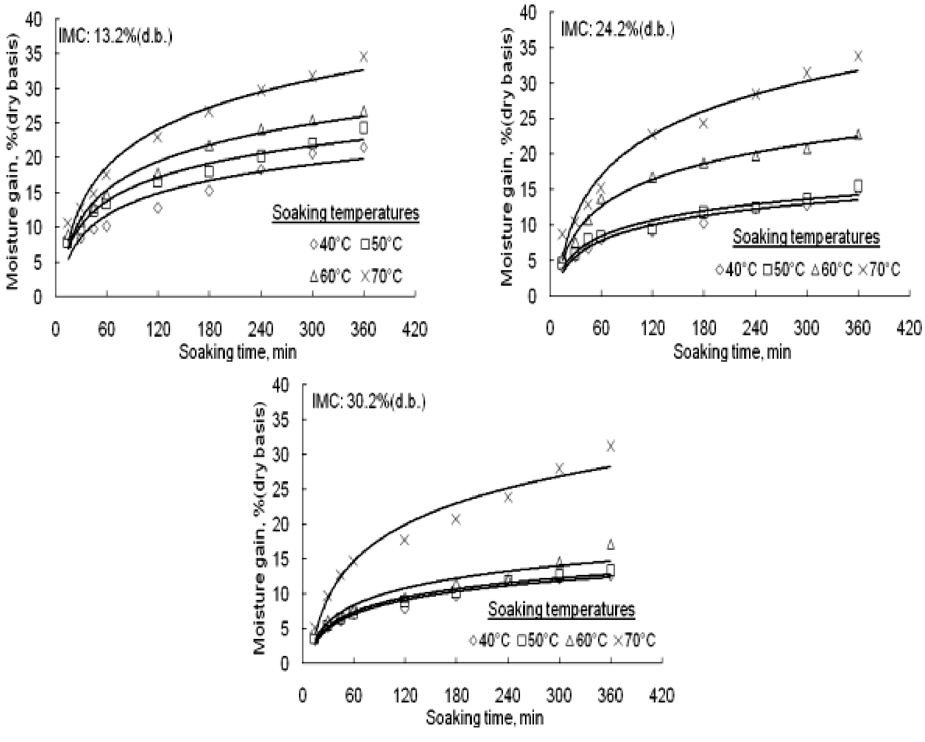

Figure 1. Moisture gain of paddy (MTU 1075) at different initial moisture contents and soaking temperatures

Hydration characteristics of paddy during steaming. The hydration curves for paddy for five levels of applied pressures, viz. 0.5, 1.0, 1.5, 2.0, 2.5 kg·cm^{-2} are shown in Fig. 3. The initial moisture contents were found out to be 13.5, 24.6 and 32.1 g per 100 g dry matter. The moisture diffusion in to the grain during steaming at these moisture levels took place at a much faster rate as compared to hot water soaking treatments. The moisture absorption rate of paddy was slower during the initial periods and it increased with increase in steaming time. Rate of moisture migration also depended upon the steam pressures and increased with the increase in steam pressure.

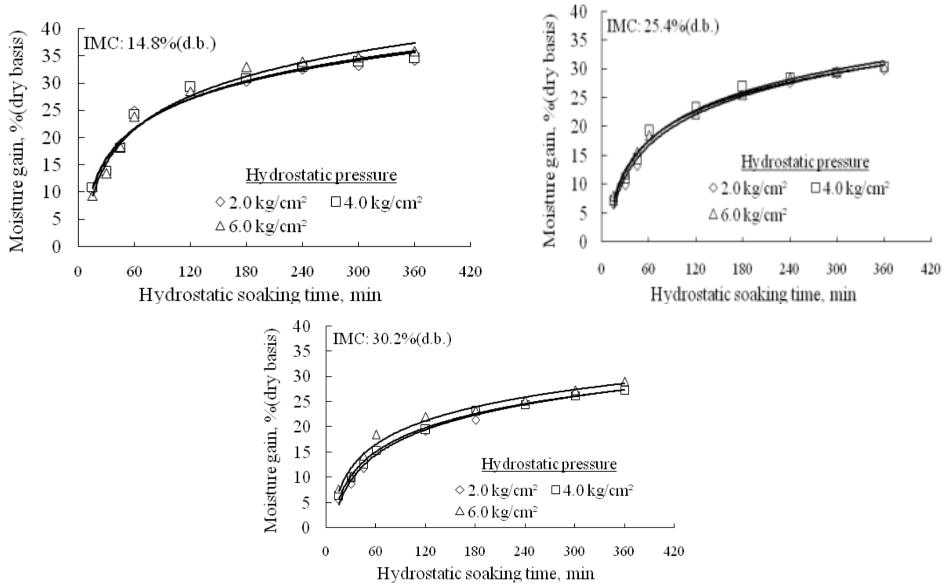

Figure 2. Moisture gain of paddy (MTU 1075) during soaking at different pressures

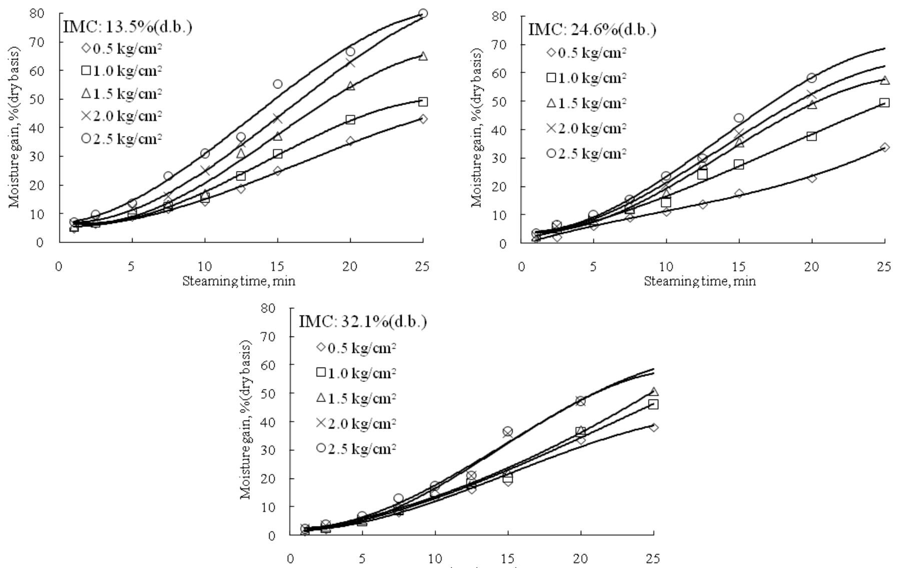

Figure 3. Moisture gain of paddy (MTU 1075) for different steaming pressures

In general, it was observed that the soaking temperature and pressure, and the steaming pressure greatly influenced the moisture absorption by the grain and in turn the time requirement for the process. Higher the pressure and temperature, less was the time requirement. However, the temperature and pressure of treatments should be decided on the basis of the final quality of parboiled grain.

Determination of diffusion coefficient. The saturation moisture contents for 40, 50, 60 and 70°C soaking temperatures remained almost constant for different durations of soaking. The maximum, minimum and mean values of the saturation moisture contents M_s along with the standard deviation values have been tabulated in Tab. 1. The mean values of M_s for all the temperatures were taken for the analysis.

Table 1. Saturation moisture contents for paddy (MTU 1075) as obtained by regression analysis for different soaking temperatures

Soaking temperature	Saturation moisture content, g per 100 g dry matter
40°C	54.2±4.8
50°C	52.3±4.9
60°C	52.4±6.8
70°C	53.5±4.2

Table 2. Diffusion coefficient of paddy (MTU 1075) during soaking under atmospheric pressure with three different initial moisture contents

Temperature [°C]	M_o=13.2 g per 100 g dry matter	M_o=24.2 g per 100 g dry matter	M_o=30.2 g per 100 g dry matter
40	1.898×10^{-06}	1.917×10^{-06}	2.431×10^{-06}
50	2.873×10^{-06}	2.150×10^{-06}	2.649×10^{-06}
60	3.702×10^{-06}	3.917×10^{-06}	3.771×10^{-06}
70	6.817×10^{-06}	1.111×10^{-05}	5.767×10^{-06}

Table 3. Diffusion coefficient of paddy (MTU 1075) at hydrostatic pressure soaking with three different initial moisture contents at 70°C

Hydrostatic pressure [kg·cm^{-2}]	M_o=14.8 g per 100 g dry matter	M_o=25.4 g per 100 g dry matter	Mo=30.2 g per 100 g dry matter
2.0	7.158×10^{-06}	9.133×10^{-06}	1.047×10^{-05}
4.0	7.010×10^{-06}	9.770×10^{-06}	1.035×10^{-05}
6.0	7.227×10^{-06}	9.944×10^{-06}	1.399×10^{-05}

Table 4. Diffusion coefficient of paddy (MTU 1075) at different steaming pressures with three different initial moisture contents

Steaming pressure [kg·cm^{-2}]	M_o=13.5 g per 100 g dry matter	M_o=24.6 g per 100 g dry matter	M_o=32.1 g per 100 g dry matter
0.5	1.119×10^{-04}	8.939×10^{-05}	2.342×10^{-04}
1.0	1.228×10^{-04}	1.971×10^{-04}	2.314×10^{-04}
1.5	2.340×10^{-04}	9.158×10^{-05}	2.744×10^{-04}
2.0	2.137×10^{-04}	1.437×10^{-04}	1.875×10^{-04}
2.5	2.678×10^{-04}	2.327×10^{-04}	2.328×10^{-04}

It was observed that the diffusion coefficient D did not exhibit any definite relationship with the initial moisture content and the moisture concentration in the grain at any time. However, the diffusion rate increased with increase in soaking or steaming temperatures. The mean values of the diffusion coefficients were taken for further calculations, which have been given in Tables 2-4. The amount of moisture migration was predicted using the average diffusion coefficient for a particular treatment.

As observed from these tables, the diffusion coefficient values during soaking varied between 1.898×10^{-6} to 1.11×10^{-5} whereas the diffusion coefficient of paddy during soaking was found to be 4.91×10^{-11} $m^2 \cdot s^{-1}$ by earlier researchers [9]. The diffusion coefficient was correlated to treatment temperature by Arrhenius type of relationship. The calculated values of diffusion coefficient *D* showed linear relationship with *1/T*, where *T* is the absolute temperature. The relationship obtained was:

$$D = 1.345\, e^{(-8407/RT)};\ R^2 = 0.9947 \quad (13)$$

The values of diffusion coefficients obtained as above for the soaking and steaming treatments have been given in Tab. 5. The diffusion constant and the activation energy were calculated to be 0.01345 $m^2 \cdot min^{-1}$ and 35.19 $kJ \cdot mole^{-1}$, respectively, whereas the activation energy of paddy soaking was observed by earlier researchers to be 31.50 $kJ \cdot mole^{-1}$ for paddy [9]. The activation energy for IR 20 paddy was also found to vary in the range of 19.49-23.09 $kJ \cdot mole^{-1}$ [10]. However, the diffusion constants were observed to be in the range of 0.406-0.647 $m^2 \cdot s^{-1}$, which was much higher as compared to the observed values.

Table 5. Average values of diffusion coefficients of paddy (Cv. MTU 1075) at different treatment conditions

Treatment temperature [K]	*Pressure [kg·cm^{-2}]*	*Diffusion coefficient (D)*
Soaking treatments		
313	*0.0*	*1.898×10^{-6}*
323	*0.0*	*2.557×10^{-6}*
333	*0.0*	*3.702×10^{-6}*
343	*0.0*	*6.817×10^{-6}*
Steaming treatments		
382	*0.5*	*2.196×10^{-5}*
391	*1.0*	*2.557×10^{-5}*
397	*1.5*	*2.988×10^{-5}*
404	*2.0*	*3.496×10^{-5}*
409	*2.5*	*4.835×10^{-5}*

It was observed that the steam pressure directly influenced the moisture absorption by the grain. Higher the pressure and temperature, lower was the time required to reach the saturation moisture content. However, the temperature and pressure of treatments should be decided on the basis of uniformity of gelatinisation and presence of white bellies in the kernels after the process.

Prediction of moisture gain at any time. Taking the average values of diffusion coefficient D at a particular soaking temperature or steaming pressure, the dimensionless parameter d was calculated using Equation 8. A regression equation was developed as below to predict the moisture ratio or $\psi(t)$.

$$MR = d_{\mathrm{pred}} 0.52\ x\ 0.782;\ R^2 = 0.98 \quad (14)$$

The predicted moisture content was then calculated using general equation

$$(Mt - Mo)_{\mathrm{pred}} = MR_{\mathrm{pred}}\ x\ (Ms - Mo) \quad (15)$$

CONCLUSIONS

The moisture diffusion characteristics of paddy (Cv. MTU 1075) were studied during soaking at different temperatures under atmospheric pressure, soaking at elevated pressures at constant temperature of 70°C and steaming at different pressures to analyse the effects of these parameters on the moisture absorption rate, diffusion coefficients and to develop the relationship between the temperature and rate of diffusion. During soaking under pressure, the moisture absorption by the grain was logarithmic in nature. Higher pressure and temperature reduced the time requirement to reach the saturation moisture content for all conditions. However, the temperature and pressure of treatments should be decided on the basis of uniformity of gelatinisation and presence of white bellies in the kernels after the process. The diffusion coefficients were found out for all the experiments, which were observed to follow Arrhenius type relationship. The diffusion constant and activation energy were found out to be 0.01345 $m^2 \cdot min^{-1}$ and 35.19 $kJ \cdot g\text{-}mole^{-1}$, respectively.

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UTICAJ TEMPERATURE I PRITISKA NA DIFUZIJU VLAGE U PIRINČU (Cv. MTU 1075)

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Sažetak: Predkuvanje je važan i energetski intenzivan postupak u preradi pirinča. Pravilan postupak može da smanji potrošnju energije i prateće troškove. Natapanje i parenje su dva glavna koraka u ovom postupku. Natapanje pirinča se obično izvodi pod atmosverskim pritiskom, što traži više vremena. Temperatura vode utiče na adsorpciju i difuziju vlage. Pritisak pri natapanju i parenju takođe utiče na process, a time i na ukupne ekonomske efekte. Karakteristike hidriranja pirinča (Cv. MTU 1075) su ispitivane pod različitim uslovima sa osnovnim ciljem da se standardizuju parametri za ove operacije. Natapanje ke izvođeno pri četiri temperature pod atmosverskim pritiskom. Hidrostatičko natapanje je izvođeno pri pritiscima od 2.0, 4.0 i 6.0 $kg \cdot cm^{-2}$ na konstantnoj temperature od 70°C. Natapanje je izvođeno pod pritiscima od 0.5, 1.0, 1.5, 2.0 i 2.5 $kg \cdot cm^{-2}$. Inicijalni sadržaj vlage pirinča varirao je na tri nivoa. Uočeno je da temperatura i pritisak natapanja i pritisak parenja utiču na adsorpciju vlage u zrno, a time i na vreme trajanja postupka. Koeficijent difuzije je bio nezavistan od inicijalne vlažnosti i pokazao je Arrhenius odnos sa temperaturom natapanja i parenja. Koeficijent difuzije pirinča varirao je u interval 8.939×10^{-5} do 2.678×10^{-4} $cm^2 \cdot min^{-1}$ za parenje pod pritiskom, 7.01×10^{-6} do 1.399×10^{-5} $cm^2 \cdot min^{-1}$ za hidrostatičko natapanje na 70°C i 1.898×10^{-6} do 1.11×10^{-5} $cm^2 \cdot min^{-1}$ za natapanje pod atmosverskim pritiskom pri različitoj temperature. Izračunata vrednost difuzione konstante je bila 0.01345 $m^2 \cdot min^{-1}$, a aktivaciona energija za difuziju vlage 35.19 $kJ \cdot g\text{-}mol^{-1}$.

Ključne reči: *predkuvanje, hidrostatičko natapanje, parenje, koeficient difuzije*

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