HEAT AND MASS TRANSFER DURING HOT-AIR DRYING OF RAPESEED: CFD APPROACH AND EVALUATION
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基于 CFD 的油菜籽热风干燥传热传质研究与验证

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ABSTRACT

Moisture content loss of rapeseed (Brassica napus L.) and drying rate change with time during thin layer hot-air drying were obtained through experiments. By means of volume weighed average, the moisture content loss of rapeseed and airflow distribution in the drying box were simulated and analyzed in FLUENT using methodology of CFD. For heat and mass transfer modelling of the rapeseed drying, a code incorporating the effects of heat and moisture transfer was compiled by means of UDFs (User-Defined Functions), and SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) scheme was adopted to solve the constitutive equations governing the rapeseed drying. Numerical findings were compared with the experimental data, and they had good agreement with experiments: mean relative errors of moisture content, air temperature and air velocity of modelling are 7.48%, 1.07% and 7.72 %, respectively.

摘要

通过实验得到了甘蓝型油菜籽在热风干燥条件下的含水率和干燥速率随时间的变化。基于 CFD 和体积加权平均，通过 FLUENT 仿真并分析了油菜籽含水率随时间的变化以及干燥室内的流场分布。为模拟油菜籽干燥的传热传质过程，通过 UDFs 编程并采用压力耦合半隐式 SIMPLE 方法求解决定干燥过程的本构方程。仿真结果和实验数据具有很好的一致性：含水率、热风温度和热风速度的平均误差分别为 7.48%、1.07%和 7.72 %。

INTRODUCTION

Rape (*Brassica campestris* L.) is an annual herbaceous plant. The stem, leaf and tender shoot of rape can be used as vegetables, and they have multiple nutritional ingredients. The blossoms are stable, being a nectar source for honeybees, and nectar of rape blossom accounts for more than 40% of total nectar production in China *(Yang et al., 2014)*.The seed is the most valuable, collected component of the crop, as the world's third leading source of vegetable oil, after soybean and oil palm, and the second leading source of protein after soybean (Yang et al., 2012). The main varieties of rape are *Brassica rapa* L., *Brassica juncea* L. and *Brassica napus* L., and Rape (*Brassica napus* L.*)* are mostly planted in Yangtze valley, China, and the seed production of rape (*Brassica napus* L.) accounts for 90% of the total *(Li et al., 2006)*.

The harvest period of rapeseed often runs into rainy season of high temperature and high humidity. The freshly harvested rapeseed contains high moisture content, then the seed may become deteriorated because of overheat, acidification and mildew, which affect physiological characteristics of the seed for seeding purpose and oil quality of the seed for oil purpose *(Yang et al., 2012)*. Yang et al. (2013) mentioned artificial drying is required to timely decrease moisture content of the rapeseed to safe levels for storage, and hot-air drying is mostly employed among numerous drying methods. For hot-air drying, hot-air functions both as heat supporter and as humidity carrier during the drying process. Uniform airflow distribution inside the drying box is of paramount importance because it determines both the efficiency of drying and the homogeneity of products being dried *(Amanlou et al., 2010)*.

Rapeseed is an unsaturated porous medium with sorptivity, and its kernel owns complex porous medium structure with biomass features. The heat and mass transfer process of rapeseed hot-air drying consists of multi-phase coupling and wet-phase transition *(Jiang et al., 2012)*. Although many experimental works are conducted on drying characteristics of rapeseed and effects of air temperature on physiological quality of the seed, little information is available on heat and mass transfer during hot-air drying of rapeseed, and it is insufficient for dryer design and process control of rapeseed drying. Thakor et al. (1999) studied the size and mass change of individual kernels of rapeseed, both whole kernel (hull attached) and embryo (kernel without hull), during drying using thermo-gravimetric analysis. Corrêa et al. (1999) experimentally studied germination and vigor response of rapeseed to air temperature and relative humidity after hot-air drying. Duc et al. (2011) conducted thin layer drying tests to determine the most appropriate thin layer drying model, effective moisture diffusivity, and activation energy for the moisture diffusion of rapeseed.

Mathematical modelling contributes to better understanding of heat and mass transfer and it is very useful for improvement of dryer design and process control of drying *(Tzempelikos et al., 2015)*. Dong-Hyuk K et al. examined the simultaneous heat and mass transfer between air and rapeseed in a concurrent-flow dryer by combined equations concerning air psychrometrics, physical properties, thermal properties, equilibrium moisture content, thin layer drying of rapeseed, etc. to solve the drying model *(Dong and Woong, 2010*). Yang L. (2004) studied heat and mass transfer process in micro pores during hot-air drying of rapeseed by means of Mixture Model of ANSYS Fluent, and analyzed effects of length to diameter ratio and tortuosity of micro pores of seed kernel on hot-air drying. Amanlou and Zomorodian (2010) applied CFD for designing a fruit cabinet, and experimental and predicted data from CFD analysis revealed good correlation coefficients. An extensive analysis of the different mathematical approaches can be found in the works of Datta, A.K. and Norton, T. et al. *(Datta et al., 2007; Norton et al., 2013)*.

The main objectives of this study are:

(1) To obtain drying characteristics of rapeseed during hot-air drying for thin layer seed experimentally.

(2) To investigate methodology of CFD for analysis of heat and mass transfer during hot-air drying of rapeseed.

(3) To compare numerical findings of the moisture content loss of rapeseed and airflow distribution in the drying box with experimental data.

MATERIAL AND METHOD

Sample preparation

The rapeseed (*Brassica napus* L.), Chuanyou 18, was bought from Chongqing Seed Company. The impurities, cracked, germinated, moldy seed and seed with green color were manually removed so as to obtain uniform test samples. The initial moisture content of rapeseed was determined according to Chinese standard GB/T14489.1-2008: Oil seeds - Determination of moisture and volatile matter content *(China National standardizing committee, 2008)*.

According to the initial moisture content of 8.7% d.b., test samples of the dry rapeseed were rewetted to moisture content of 15% d.b., by adding pre-calculated amount of water, mixed, sealed with plastic bags, and kept in a temperature controlled room at temperature of 2-4°C for no less than 48 h. Before starting experiments, they were taken out from the controlled room and let them attain thermal equilibrium with ambient air.

Experimental setup and procedure

Experiments were conducted in a lab-scale thin layer dryer as shown in fig. 1.

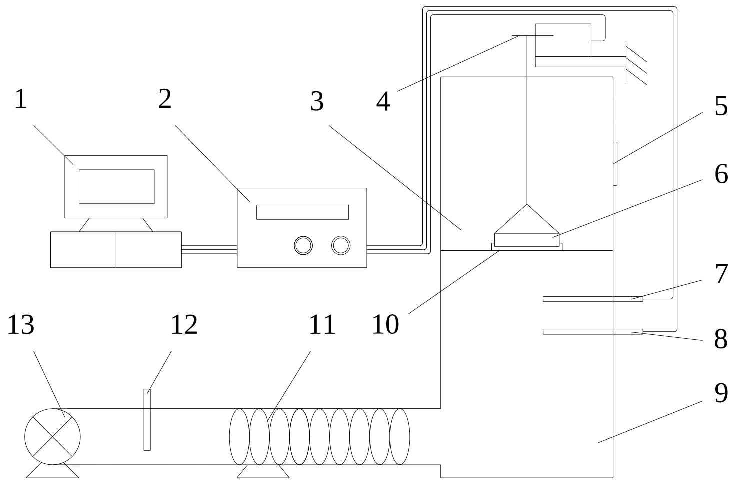


Fig. 1 - Schematic diagram of the thin layer dryer

1 – Computer; 2 - Data acquisition; 3 - Drying box; 4 - Load cell; 5 – Exit; 6 - Sieve tray; 7 - Temperature sensor; 8 - Humidity sensor; 9 - Plenum chamber; 10 – Entrance; 11 - Heater; 12 - Valve; 13 - Fan

The experimental setup consists of fan, heater, valve, drying box, load cell, temperature sensor, humidity sensor, data acquisition and computer. Sieve tray with a holding area of 150 mm × 150 mm is included in the drying box. The cube drying box dimensions are of side length 400 mm. Exit of the drying box is of diameter 100 mm. The mass flow rate and heat flow rate of hot-air are regulated by the valve, and the heater, respectively.

The test samples of rapeseed, weighing about 420 g with a seed layer thickness of 20 mm, were placed in the sieve tray. During the drying process, the samples were periodically weighed to determine weight loss at 5 min intervals, from which the drying curves were obtained. The drying rate is determined by *(Zhang et al., 2012)*:

$$DR = -\frac{dW}{dt} = -\frac{W_{i+1} - W_i}{t_{i+1} - t_i}, \text{ [d.b./s]} \tag{1}$$

where:

DR is drying rate of rapeseed, [d.b./s];

W – moisture content of seed in dry basis, [d.b.];

t – time, [s];

W_i – moisture contents at t_i, [d.b.];

W_{i+1} – moisture contents at t_{i+1}, [d.b.].

The additional measurements included air temperature and air velocity at 3 different positions, namely top of seed layer, centre and exit of the drying box, and the measurements are for the validation of experimental data and numerical findings of rapeseed hot-air drying. All measurements are of 5 replicas. The measuring instruments are the portable thermometer (DS18B20, Beijing Chuangyiling Control Co. Ltd, China) and the anemometer (SUMMIT-565, Guangzhou Taishi Instrument Co. Ltd, China).

Methodology for modelling and evaluation

In order to model the heat and mass transfer during hot-air drying of rapeseed with simplicity and good validity, the relevant assumptions are described as follows *(Jamaleddine and Ray, 2010)*:

The gas phase is a mixture of air and water vapour. The dispersed phase is a mixture of porous homogeneous structure and liquid water. Both phases are incompressible.

Heat transfer occurs between both phases, and is no heat transfer between phases and walls of the drying box.

There is no shrinkage and deformation of rapeseed kernels, and only water evaporation during drying process.

There are no cohesive moves of rapeseed and effects of cohesive dissipation heat and thermal radiation are not considered.

The hot temperature of air causes heat transfer from carrier, namely hot-air, to rapeseed, while evaporation from water to vapour occurs from the rapeseed to gas phase. Constitutive equations describing the mass and heat transfer are as follows *(Thorpe et al., 2008)*.

The mass transfer equation is:

$$\frac{\partial(\rho_a w)}{\partial t} + \nabla\cdot(\rho_a v w) = \nabla\cdot(\rho_a D_{eff} \nabla w) + S_w \tag{2}$$

where:

ρ_a is density of air, [kg/m^3];

w – moisture content of air, [d.b.];

v – superficial or Darcian velocity of air through seed, [m/s];

D_{eff} – effective diffusion coefficient of moisture through bulk seed, [m^2/s];

S_w – moisture source term, [kg/(s·m^3)];

∇ – the del operator.

The heat transfer equation is:

$$\left(\rho_a \varepsilon c_a + \rho_s (1-\varepsilon)\left(c_s + c_w W + \frac{\partial H_w}{\partial T}\right)\right)\frac{\partial T}{\partial t} + c_a \nabla\cdot(\rho_a u T) = k_{eff}\nabla^2 T + S_h \tag{3}$$

where:

ε is void fraction of seed;

c_a, c_s, c_w – specific heat of air, seed and liquid water, respectively, [J/(kg·K)];
ρ_s – density of seed kernels in dry basis, [kg/m^3];
H_W – integral heat of wetting of water on seed, [J/kg];
T – temperature, [K];
k_{eff} – effective thermal conductivity of seed, [W/(m·K)];
S_h – energy source term, [W/m^3].

The moisture source term S_w in Eq. 2 is expressed as:

$$S_w = -(1-\varepsilon)\rho_s \frac{\partial W}{\partial t}, \text{ [kg/(s·m}^3\text{)]} \tag{4}$$

The energy source term S_h in Eq. 3 takes the form:

$$S_h = -h_s(1-\varepsilon)\rho_s \frac{\partial W}{\partial t}, \text{ [W/m}^3\text{]} \tag{5}$$

where:

h_s is heat of sorption of water on seed, J/kg.

The physical configuration of the drying box for modelling is represented and meshed as shown in fig. 2. The physical configuration has same dimensions as drying box of the thin layer hot-air dryer mentioned above.

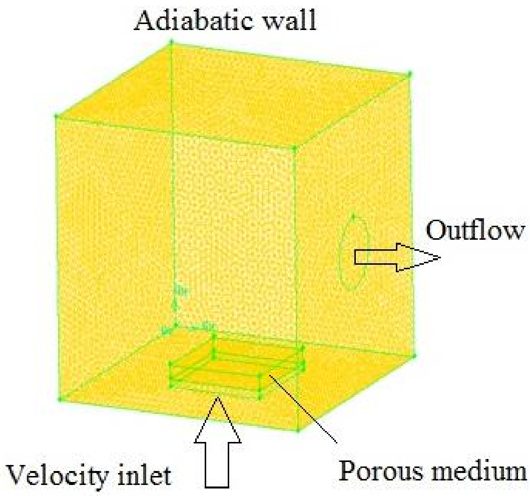


Fig. 2 - Physical configuration, meshing of the drying box

The corresponding boundary and initial conditions are defined as follows: Air in the drying box is defined as fluid, and rapeseed on the sieve tray as porous medium. The initial temperature of rapeseed is 298 K. Entrance of the drying box is defined as velocity inlet, and exit as outflow. The air velocity and temperature of hot-air at entrance of the drying box are 1.0 m/s and 373 K, respectively. Walls of the drying box are defined as adiabatic wall. Interface between fluid and porous medium is defined as interior.

The physical properties of air and rapeseed for the modelling are listed in table 1.

Table 1

Physical properties of air and rapeseed

Properties	**Air**	**Rapeseed**
Density, [kg·m^3]	1.225	945.5
Specific heat, [J·kg^{-1}·K^{-1}]	1006.43	1561
Thermal conductivity, [W·m^{-1}·K^{-1}]	0.0242	0.169
Viscosity, [Pa·s]	1.7894×10^{-5}	-
Viscous resistance, [m^{-2}]	-	5.9×10^8
Inertial resistance, [m^{-1}]	-	3.2×10^4
Porosity, [%]	-	36

In order to better demonstrate the coupling of heat and mass transfer during hot-air drying, a code incorporating the effects of heat and mass transfer was compiled by means of UDFs (User-Defined Functions) in a high level language of C. Reference of strategy for the code writing, with small modification, was given to Thorpe's work *(Thorpe G.R., 2008)*. SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) scheme was adopted to solve the constitutive equations governing the rapeseed hot-air drying in FLUENT.

For visual analysis of the CFD data and further explorations of the rapeseed hot-air drying, post-processor of Tecplot 360 was employed to plot the contours of air velocity and air temperature in the drying box.

The relative error of modelling with experiments is evaluated by:

$$E = \frac{|D_M - D_E|}{D_E} \times 100\% \tag{6}$$

where:

E is relative error, [%];

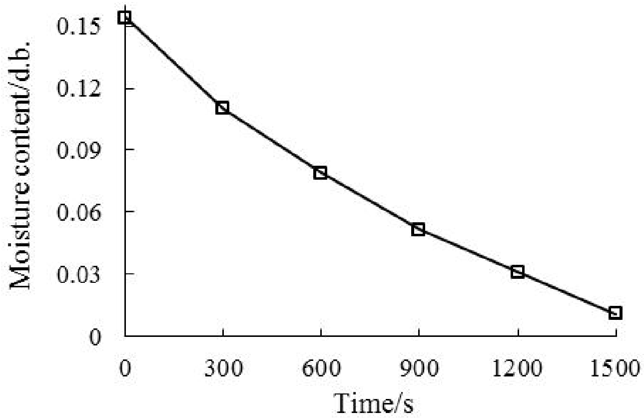
D_M, D_E – interested parameters from modelling and experiments, respectively.

RESULTS

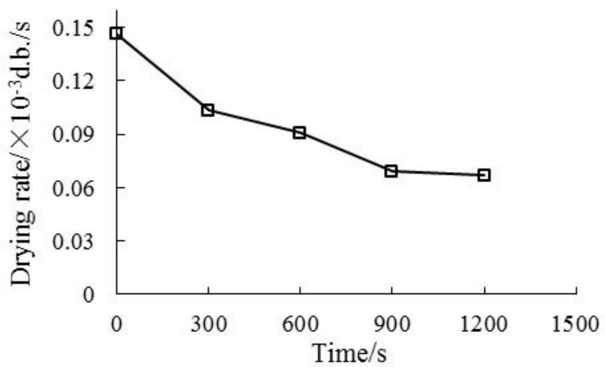
Experimental results

The drying behavior can be characterized by measuring the moisture content loss as a function of time.

The drying characteristics of rapeseed during thin layer hot-air drying are represented by the moisture content loss curve and the drying rate curve as shown in fig. 3. The conditions for the experiment are as follows: seed layer thickness of 20 mm, air velocity of 1.0 m/s, and air temperature of 373 K.



(a) Moisture content loss curve



(b) Drying rate curve

Fig. 3 - Drying characteristics of rapeseed by the experiment

Air temperature, air velocity and their distribution are important factors affecting the drying behavior of rapeseed.

The air temperature and air velocity at 3 representative positions of the drying box were measured at 5 min intervals as shown in fig. 4 and fig. 5, respectively.

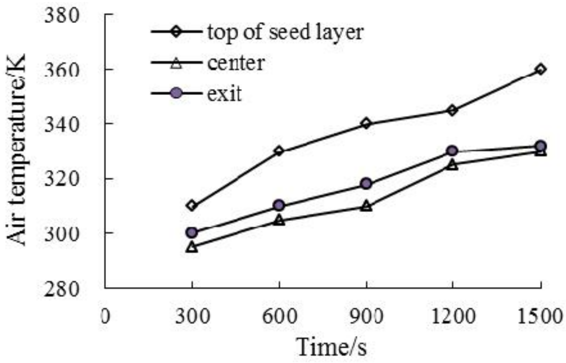


Fig. 4 - Air temperature at different positions of drying box

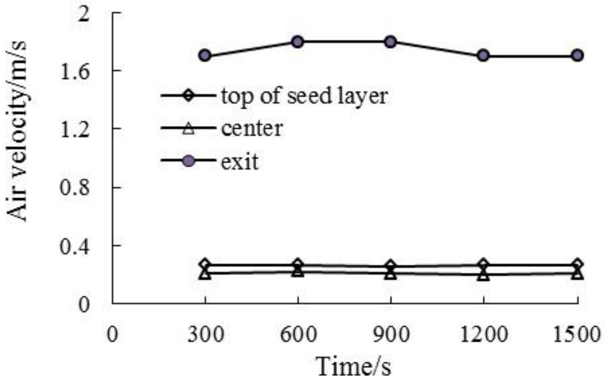


Fig. 5 - Air velocity at different positions of drying box

Modelling results of rapeseed drying

The moisture content loss of rapeseed can be obtained by modelling as shown in fig. 6. It is the volume weighed average of porous medium of the rapeseed in the drying box. The volume weighted average of a quantity is computed by dividing the summation of the product of the selected field variable and cell volume by the total volume of the cell zone in ANSYS Fluent.

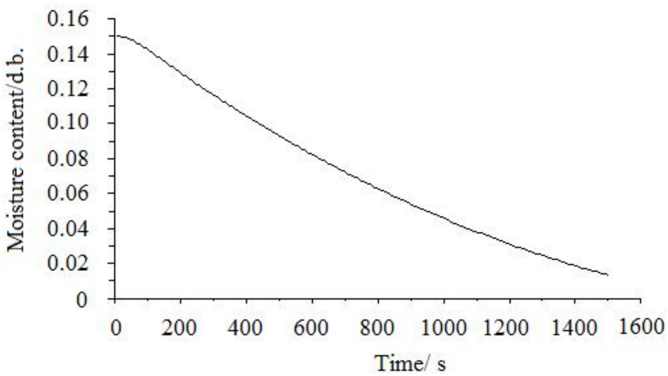
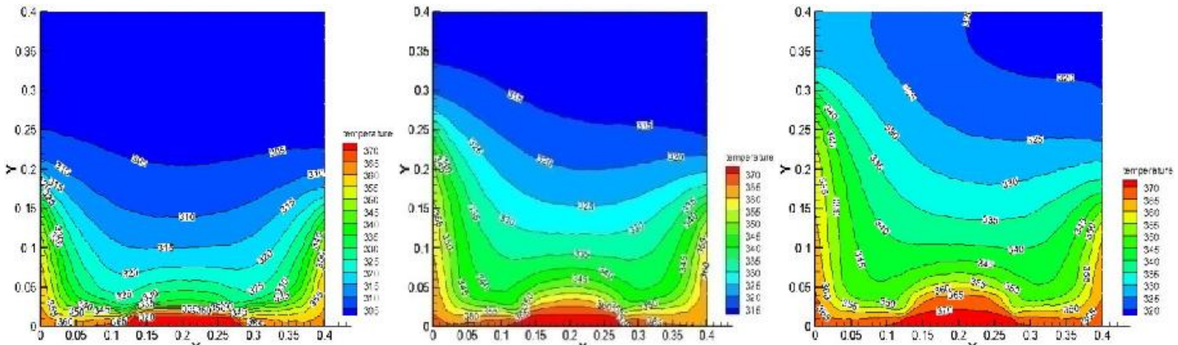


Fig. 6 - Moisture content loss curve by modeling

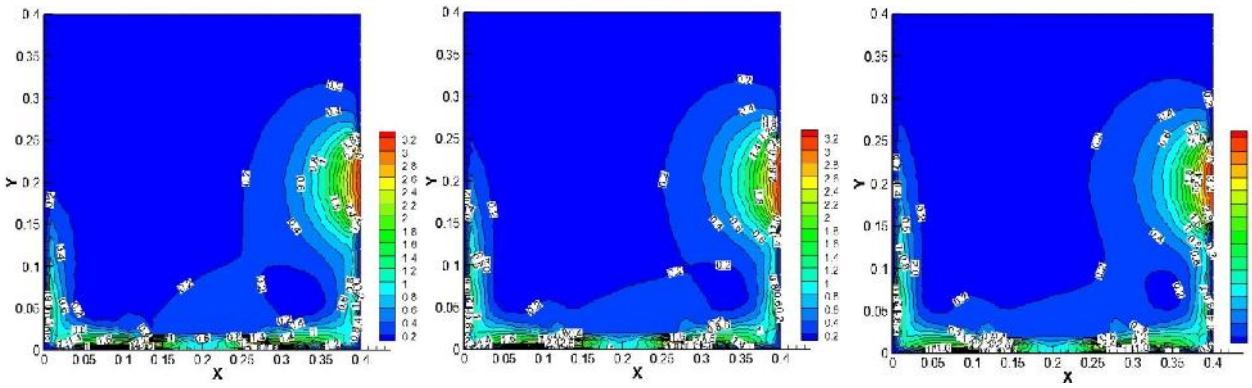
The flow parameters of the rapeseed during thin layer hot-air drying can be visualized by post processing. As the drying box has symmetrical geometry along vertical plane passing through axis of the exit of drying box, the contours of air temperature and air velocity on this plane are representatively plotted as shown in fig.7 and fig.8, respectively. The time intervals interested for the plotting are 600, 1200, and 1500 s.

For the contours in fig. 7 and fig. 8, the *X* axis is along horizontal direction, and the *Y* axis is along vertical direction, showing the dimensions of the drying box. The colours in the contours depict the difference of parameters interested at different areas in the drying box, and the scales at the side of each contour illustrate the values of parameter at the corresponding area. As a result, changes of air temperature and air velocity in the drying box with the progress of hot-air drying are visually described.



(a) 600 s (b) 1200 s (c) 1500 s

Fig. 7 - Air temperature contour of time intervals



(a) 600 s (b) 1200 s (c) 1500 s

Fig. 8 - Air velocity contour of time intervals

Analysis and discussion

The moisture content loss curves of rapeseed thin layer hot-air drying showed that there is no constant rate drying stage for rapeseed, as shown in Figures 3 and 6. The moisture contents of rapeseed are 11.3%, 7.5%, 5.2%, 3.2% and 1.2% d.b. at 300, 600, 900, 1200 and 1500 s. The drying conditions are air temperature 373 K, air velocity 1.0 m/s, initial moisture content of rapeseed 15% d.b. and layer thickness 20 mm. The moisture transfer of rapeseed is mainly occurred in the former stage, and the drying rate decreases with drying process continued. The moisture content (MC) of rapeseed from modelling and experiments and their relative error are listed in table 2.

Table 2

Relative error of moisture content

Time [s]	MC from modelling [% d.b.]	MC from experiments [% d.b.]	Relative error [%]
300	11.8	11.3	4.4
600	8.1	7.5	6.8
900	5.0	5.2	3.9
1200	2.9	3.2	6.4
1500	1.0	1.2	16.0

The distribution of air temperature in the drying box gradually changes with the drying process continued, and the air temperature at the top of seed layer is much higher than that at centre and exit of the drying box, of which benefits the rapeseed thin layer hot-air drying. The distribution of air velocity reaches a stable status in quite a short period of time, and the air velocities at the top of seed layer and centre of the drying box are nearly same, but with a small loss at centre position, and the air velocity at the exit of the drying box is much higher than those at positions of the former two. The air temperature, air velocity from modelling and experiments, and their relative error, at different positions and process time are listed in tables 3 and 4.

Commercial CFD packages are capable of solving the general constitutive equations that govern conservation of mass, energy and momentum and they must be tailored so that heat, moisture and airflow distributions during drying of porous medium can be obtained. User-Defined Function is a successful approach to model the heat and mass transfer during thin layer hot-air drying of rapeseed for CFD. The moisture content and airflow distributions obtained from modelling showed considerably good agreement with those from experiments: mean relative error of moisture content of modeling with experiments is 7.48%; mean relative errors of air temperature and air velocity are 1.07% and 7.72%, respectively.

By methodology of CFD modelling of the hot-air drying, the following performance parameters or feathers can also be obtained: the time for drying certain amount of rapeseed of pre-measured moisture content to required moisture level; the performance of rapeseed drying with temperature-change technological process, namely different drying stages having different air temperatures; the airflow distribution, including air temperature, air velocity, and pressure, etc., of a drying box with different geometry. Therefore, the technological process and its control strategy of thin-layer hot-air drying of rapeseed, and the structure and parameters of the drying box can be optimized by modelling, which can provide reference and basis for optimization of drying technique and equipment of rapeseed hot-air drying.

Table 3

Relative error of air temperature

Position	Time [s]	Temperature from modelling, [K]	Temperature from experiments, [K]	Relative error, [%]
Top of seed layer	600	325	328	0.9
	1200	345	343	0.5
	1500	355	350	1.4
Centre	600	310	305	1.6
	1200	320	325	1.5
	1500	330	328	0.6
Exit	600	315	310	1.6
	1200	335	330	1.5
	1500	340	340	0

Table 4

Relative error of air velocity

Position	Time, [s]	Velocity from modelling, [$m \cdot s^{-1}$]	Velocity from experiments, [$m \cdot s^{-1}$]	Relative error, [%]
Top of seed layer	600	0.30	0.27	11.0
	1200	0.30	0.27	11.0
	1500	0.29	0.27	11.0
Centre	600	0.20	0.22	9.0
	1200	0.20	0.20	0
	1500	0.20	0.21	4.7
Exit	600	1.60	1.80	11.0
	1200	1.80	1.70	5.9
	1500	1.80	1.70	5.9

CONCLUSIONS

In this study, a numerical investigation of heat and mass transfer during thin layer hot-air drying of rapeseed was carried out, and the experimental measurements were taken for the respective drying conditions. The following conclusions can be drawn from the results of this study:

(1) There is no constant rate drying stage for the thin layer hot-air drying of rapeseed. The moisture transfer of rapeseed is mainly occurred in the former stage, and the drying rate decreases with drying process continued.

(2) User-Defined Function is a successful approach to model the heat and mass transfer during thin layer hot-air drying of rapeseed for CFD, and the moisture content loss of rapeseed and airflow distributions in the drying box can be obtained from the modelling.

(3) Numerical findings had good agreement with experiments: mean relative error of moisture content is 7.48%, and mean relative errors of air temperature and air velocity are 1.07% and 7.72%.

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