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Simple Modelling of Static Drying of RDX

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Abstract

The effect of drying temperature on drying rates of RDX was investigated at different temperature. The increasing of temperature ranging from 60 to 90℃ dramatically contributed to the improvement of drying rate as well as a significant decrease in drying time. The experimental drying data were applied to 10 various thin-layer drying models. Among the proposed models, Midilli-Kucuk model was the best for characterizing drying behavior of RDX for the whole range of temperature. The variations of these models parameters with temperature were described as Arrhenius and Logarithmic type function of drying temperature. A series of model equations disclosing the temperature and time dependence of static drying of RDX was derived, which were determined by multiple regression analysis. Model 35 derived from Two term model has the lowest RMSE, MBE and chi-square and the highest modeling efficiency and regression coefficient. The moisture ratio change during static drying of RDX in the temperature range of 60-90℃ was also put forward.

Keywords: RDX; Static Drying; Thin-layer Models; Statistical Test

1 INTRODUCTION

Currently, the domestic main production technology of RDX is direct nitrolysis, the RDX obtained by means of this pathway may contain some impurities, such as mechanical impurities, organic impurities, solvent and residual moisture, in which mechanical impurities, organic impurities, solvent mainly result from external environment and device condition, and the content of these impurities is easy to control and adjust. On the contrary, moisture esp. water always exists throughout the entire preparation process of RDX and the removal of water usually is undergone by vacuum static drying characterized by large energy-consumption and low efficiency. Consequently, the content of water in RDX is higher than that in other ones. The contained water in RDX has such an important influence on properties of RDX that increasing moisture content would result in lower detontion performances, worse storage and unexpected security risk, etc. Therefore, drying is extremely essential and important for RDX. Drying is a worldwide focus of considerable importance, which is a complicated process involving simultaneous transfer and coupling of heat and mass. Most of released literatures [1-3] paid attention to drying of products in the field of food, agriculture, forestry and so on, and little discussion has not been reported with respected to profound analysis of temperature affecting drying process of RDX. As an energetic material, RDX is easy and sensitive to blast under the action of external energy, such as heat energy, electric energy, light energy, mechanical energy with which a lot of heat energy and gas with high tempera mechanical sensitivity of RDX leads to another different drying method from ordinary drying commonly adopted in the dehydration of non- energetic material.

Conventional explosive drying[4] is conducted in a vacuum drying cabinet, using 90-100 ℃ hot water as a heating source, then evenly distributing material on the aluminum plate in a drying cabinet, and drying in a negative pressure environment (not less than 400 mm Hg column) to a moisture content less than 0.1%, and for the passivation RDX. In order to keep phlegmatizing agents coated on surface of RDX from aging and melting, hot water temperature should be lower, about 70-80 ℃, accordingly the drying time is accordingly longer, about 18-20 hours. Static tray drying belonging to the field of the traditional indirect contact conduction drying, is featured with low drying rate as well as long cycle, meanwhile, for the purpose of increasing the heat transmission area and the heat transmission coefficient, it is necessary to artificially create new heating surface, resulting in relatively complex equipment

structure. Subsequently, researchers introduce fluidized bed into the drying of RDX, ventilation with hot air flow to make wet particle in a state of suspension, fluidized bed into the drying of RDX along with hot air flow to make wet particle in a state of suspension are introduced as fluidized boiling is helpful for heat exchange of material through the hot air flow carrying the evaporative water away. Compared with conventional drying, such drying style of gas-solid with two phase suspension contacting heat and mass transfer adequately contacts the hot air with wet materiel and enhances the process of heat transfer and mass transfer, greatly improving the drying rate and production capacity. Besides, the employed equipment is relatively simple, easy to operate for workers, releasing workers ecstatically. However, there always two sides to everything that fluidized bed drying of RDX is liable to generate a large number of RDX dust and causes the difficulty in increasing subsequent dust recovery strength, dust handling and exhaust air; what's more in details, there will be electrostatic caused by collision and friction between dust particles and hot air , which would automatically discharge electric spark, once triggered in a sudden, accidental combustion and explosion，when accumulated to a certain extent, so, based on the above analysis, this method was not formally applied in industrial production. In recent years, based on proved survey that explosives are insensitive to microwave[5-8], whose radiation was used for the drying experiments of ultrafine RDX and submicron TATB explosives, the results show that microwave drying of explosives, in contrast with normal conduction heating, can greatly improve the drying efficiency, reduce the drying time, and avoid the agglomeration of ultrafine particles, and the feasibility that microwave drying replaced low-temperature drying and high temperature drying was proposed[9-10]

The research for drying technological conditions of RDX has remarkable significance for further study of drying, producing, storage technology of RDX and other energetic materials. As the drying process of RDX is obliged by many factors, in this work, the effect of drying temperature on drying rates of RDX was debated at different temperature, and the corresponding drying model was also presented.

2 EXPERIMENTAL APPARATUS AND METHODS

2.1 Experimental apparatus

The investigative mixtures prepared for containing RDX and water with proportions 8% (dry basis) were chosen in the thin-layer drying experiment. The research was conducted in DZF 2001 vacuum drying oven with 220V for voltage of power, 400W for power consuming, 50～200℃ for temperature range, ±1℃ for temperature fluctuations, 300×300×275 for the size of drying studio. JA2003B electronic balance with precise 0.001g was used to measure the weight of matter dried.

2.2 Static drying experiment [11-12]

In static drying experiment, the testing material was dried at 60, 70, 80 and 90℃, respectively, in the vacuum dryer after the dryer reached steady state conditions. RDX was spread in a single layer on the tray and the absolute pressure in the dryer was 0.00MPa. Moisture losses of sample were recorded at 5 min interval by the digital balance of 0.001 g accuracy. It was considered that the dry product obtained an equilibrium condition with the atmosphere inside the drying chamber when the constant weight at three consecutive times was attained. The moisture content at that time was considered as the equilibrium moisture content. Each experiment was replicated three times and the average values were used for analysis.

2.3 Mathematical modelling of static drying curves

Static drying curves were fitted with 10 different empirical and semi-empirical drying models [13-15] (TABLE 1). The regression analysis was performed using STATISTICA routine. Average regression coefficient (rave) and chi-square were primary criterion for selecting the most suitable equation to describe the static drying curves. The effects of temperature on the constants and coefficients (coc) of these models in Table 1 were examined by multiple combinations of the different equations as Arrhenius and Logarithmic types.

$$\text{Arrhenius: } coc = k_0 \exp(-k_1 / RT) \tag{1}$$

$$\text{Logarithmic: } coc = k_0 + k_1 \ln T \tag{2}$$

Therefore, nm new models can be obtained from Table 1. Where m is the total number of constants and coefficients in the model and n expresses the number of combination equations. In this way, 68 new equations given in TABLE 2 were derived, whose performance was evaluated using various statistical parameters such as the mean bias error (MBE), the root mean square error (RMSE) and the mean square of deviations (χ^2) and the modelling efficiency (EF) in addition to R. These parameters are expressed according to the following relations:

$$\text{MBE}=\frac{\sum_{i=1}^{N}(\text{MR}_{\text{pre,i}}-\text{MR}_{\text{exp,i}})}{N} \tag{3}$$

$$\text{RMSE}=[\frac{\sum_{i=1}^{N}(\text{MR}_{\text{pre,i}}-\text{MR}_{\text{exp,i}})^2}{N}]^{1/2} \tag{4}$$

$$\chi^2=\frac{\sum_{i=1}^{N}(\text{MR}_{\text{exp,i}}-\text{MR}_{\text{pre,i}})^2}{N-\text{n}} \tag{5}$$

$$EF=1-\frac{\sum_{i=1}^{N}(\text{MR}_{\text{pre,i}}-\text{MR}_{\text{exp,i}})^2}{\sum_{i=1}^{N}(\text{MR}_{\text{exp,i}}-\text{MR}_{\text{exp,ave}})^2} \tag{6}$$

Where $MR_{exp,i}$ is the ith experimental moisture ratio, $MR_{exp,ave}$ is the mean of experimental moisture ratio values. $MR_{pre,i}$ is the ith predicted moisture ratio, N is the number of observations, s in thn is the number of constant drying model.

TABLE 1 THE PRINCIPAL THIN-LAYER DRYING MODELS

Model no.	Model name	Model equation
1	Newton	$MR=\exp(-kt)$
2	Page	$MR=\exp(-kt^N)$
3	Henderson and Pabis	$MR=a\exp(-kt)$
4	Modified Page	$MR=\exp(-(kt)^N)$
5	Logarithmic	$MR=a\exp(-kt)+c$
6	Two term model	$MR=a\exp(-kt)+b\exp(-k_0t)$
7	Two-term exponential	$MR=a\exp(-kt)+(1-a)\exp(-kat)$
8	Wang and Singh	$MR=1+at+bt^2$
9	Approximation of diffusion	$MR=a\exp(-kt)+(1-a)\exp(-kbt)$
10	Midilli-Kucuk	$MR=a\exp(-kt^N)+bt$

TABLE 2 MODELS DERIVED FROM MODELS IN TABLE 1

Derived	No.	Model
Newton	1	$\text{MR}=\exp(-(\text{k}_0\exp(\frac{-\text{k}_1}{\text{RT}}))\text{t})$
	2	$MR=\exp(-(k_0+k_1\ln T)t)$
Page	3	$MR=\exp(-(k_0\exp(\frac{-k_1}{RT}))t^{N_0\exp(\frac{-N_1}{RT})})$
	4	$MR=\exp(-(k_0+k_1\ln T)t^{N_0\exp(\frac{-N_1}{RT})})$
	5	$MR=\exp(-(k_0\exp(\frac{-k_1}{RT}))t^{N_0+N_1\ln T})$
	6	$MR=\exp(-(k_0+k_1\ln T)t^{N_0+N_1\ln T)})$

TABLE 2 MODELS DERIVED FROM MODELS IN TABLE 1(CONT.)

Derived	No.	Model
Henderson and Pabis	7	$MR = a_0 \exp(\frac{-a_1}{RT}) \exp(-(k_0 \exp(\frac{-k_1}{RT}))t)$
	8	$MR = (a_0 + a_1 \ln T) \exp(-(k_0 \exp(\frac{-k_1}{RT}))t)$
Henderson and Pabis	9	$MR = a_0 \exp(\frac{-a_1}{RT}) \exp(-(k_0 + k_1 \ln T)t)$
	10	$MR = (a_0 + a_1 \ln T) \exp(-(k_0 + k_1 \ln T)t)$
Modified Page	11	$MR = \exp(-((k_0 \exp(\frac{-k_1}{RT}))t)^{N_0 \exp(\frac{-N_1}{RT})})$
	12	$MR = \exp(-((k_0 + k_1 \ln T)t)^{N_0 \exp(\frac{-N_1}{RT})})$
	13	$MR = \exp(-(k_0 \exp(\frac{-k_1}{RT})t)^{N_0 + N_1 \ln T})$
	14	$MR = \exp(-((k_0 + k_1 \ln T)t)^{N_0 + N_1 \ln T)})$
Logarithmic	15	$MR = a_0 \exp(\frac{-a_1}{RT}) \exp(-(k_0 \exp(\frac{-k_1}{RT}))t) + c_0 \exp(\frac{-c_1}{RT})$
	16	$MR = (a_0 + a_1 \ln T) \exp(-(k_0 \exp(\frac{-k_1}{RT}))t) + c_0 \exp(\frac{-c_1}{RT})$
	17	$MR = a_0 \exp(\frac{-a_1}{RT}) \exp(-(k_0 + k_1 \ln T)t) + c_0 \exp(\frac{-c_1}{RT})$
	18	$MR = (a_0 + a_1 \ln T) \exp(-(k_0 + k_1 \ln T)t) + c_0 \exp(\frac{-c_1}{RT})$
	19	$MR = a_0 \exp(\frac{-a_1}{RT}) \exp(-(k_0 \exp(\frac{-k_1}{RT}))t) + (c_0 + c_1 \ln T)$
	20	$MR = (a_0 + a_1 \ln T) \exp(-(k_0 \exp(\frac{-k_1}{RT}))t) + (c_0 + c_1 \ln T)$
	21	$MR = a_0 \exp(\frac{-a_1}{RT}) \exp(-(k_0 + k_1 \ln T)t) + (c_0 + c_1 \ln T)$
	22	$MR = (a_0 + a_1 \ln T) \exp(-(k_0 + k_1 \ln T)t) + (c_0 + c_1 \ln T)$
Two term model	23	$MR = a_0 \exp(\frac{-a_1}{RT}) \exp(-(k_0 \exp(\frac{-k_1}{RT}))t) + b_0 \exp(\frac{-b_1}{RT}) \exp(-(k_2 \exp(\frac{-k_3}{RT}))t)$
	24	$MR = (a_0 + a_1 \ln T) \exp(-(k_0 \exp(\frac{-k_1}{RT}))t) + b_0 \exp(\frac{-b_1}{RT}) \exp(-(k_2 \exp(\frac{-k_3}{RT}))t$
	25	$MR = a_0 \exp(\frac{-a_1}{RT}) \exp(-(k_0 + k_1 \ln T)t) + b_0 \exp(\frac{-b_1}{RT}) \exp(-(k_2 \exp(\frac{-k_3}{RT}))t$
	26	$MR = (a_0 + a_1 \ln T) \exp(-(k_0 + k_1 \ln T)t) + b_0 \exp(\frac{-b_1}{RT}) \exp(-(k_2 \exp(\frac{-k_3}{RT}))t$
	27	$MR = a_0 \exp(\frac{-a_1}{RT}) \exp(-(k_0 \exp(\frac{-k_1}{RT}))t) + (b_0 + b_1 \ln T) \exp(-(k_2 + k_3 \ln T)t)$
	28	$MR = (a_0 + a_1 \ln T) \exp(-(k_0 \exp(\frac{-k_1}{RT}))t) + (b_0 + b_1 \ln T) \exp(-(k_2 + k_3 \ln T)t)$
	29	$MR = a_0 \exp(\frac{-a_1}{RT}) \exp(-(k_0 + k_1 \ln T)t) + (b_0 + b_1 \ln T) \exp(-(k_2 + k_3 \ln T)t)$
	30	$MR = (a_0 + a_1 \ln T) \exp(-(k_0 + k_1 \ln T)t) + (b_0 + b_1 \ln T) \exp(-(k_2 + k_3 \ln T)t)$

TABLE 2 MODELS DERIVED FROM MODELS IN TABLE 1(CONT.)

Derived	No.	Model
Two term model	31	$MR = a_0 \exp(\frac{-a_1}{RT}) \exp(-(k_0 \exp(\frac{-k_1}{RT}))t) + (b_0 + b_1 \ln T) \exp(-(k_2 \exp(\frac{-k_3}{RT}))t)$
	32	$MR = (a_0 + a_1 \ln T) \exp(-(k_0 \exp(\frac{-k_1}{RT}))t) + (b_0 + b_1 \ln T) \exp(-(k_2 \exp(\frac{-k_3}{RT}))t$
Two term model	33	$MR = a_0 \exp(\frac{-a_1}{RT}) \exp(-(k_0 + k_1 \ln T)t) + (b_0 + b_1 \ln T) \exp(-(k_2 \exp(\frac{-k_3}{RT}))t$
	34	$MR = (a_0 + a_1 \ln T) \exp(-(k_0 + k_1 \ln T)t) + (b_0 + b_1 \ln T) \exp(-(k_2 \exp(\frac{-k_3}{RT}))t$
	35	$MR = a_0 \exp(\frac{-a_1}{RT}) \exp(-(k_0 \exp(\frac{-k_1}{RT}))t) + b_0 \exp(\frac{-b_1}{RT}) \exp(-(k_2 + k_3 \ln T)t)$
	36	$MR = (a_0 + a_1 \ln T) \exp(-(k_0 \exp(\frac{-k_1}{RT}))t) + b_0 \exp(\frac{-b_1}{RT}) \exp(-(k_2 + k_3 \ln T)t)$
	37	$MR = a_0 \exp(\frac{-a_1}{RT}) \exp(-(k_0 + k_1 \ln T)t) + b_0 \exp(\frac{-b_1}{RT}) \exp(-(k_2 + k_3 \ln T)t)$
	38	$MR = (a_0 + a_1 \ln T) \exp(-(k_0 + k_1 \ln T)t) + b_0 \exp(\frac{-b_1}{RT}) \exp(-(k_2 + k_3 \ln T)t)$
Two-term exponential	39	$MR = a_0 \exp(\frac{-a_1}{RT}) \exp(-(k_0 \exp(\frac{-k_1}{RT}))t) + (1\text{-}a_0 \exp(\frac{-a_1}{RT})) \exp(-(k_0 \exp(\frac{-k_1}{RT}))a_0 \exp(\frac{-a_1}{RT})t)$
	40	$MR = (a_0 + a_1 \ln T) \exp(-(k_0 \exp(\frac{-k_1}{RT}))t) + (1\text{-}(a_0 + a_1 \ln T)) \exp(-(k_0 \exp(\frac{-k_1}{RT}))(a_0 + a_1 \ln T)t)$
	41	$MR = a_0 \exp(\frac{-a_1}{RT}) \exp(-(k_0 + k_1 \ln T)t) + (1\text{-}a_0 \exp(\frac{-a_1}{RT})) \exp(-(k_0 + k_1 \ln T)a_0 \exp(\frac{-a_1}{RT})t)$
	42	$MR = MR = (a_0 + a_1 \ln T) \exp(-(k_0 + k_1 \ln T)t) + (1\text{-}(a_0 + a_1 \ln T)) \exp(-(k_0 + k_1 \ln T)(a_0 + a_1 \ln T)t)$
Wang and Singh	43	$MR = 1 + (a_0 \exp(\frac{-a_1}{RT}))t + (b_0 \exp(\frac{-b_1}{RT}))t^2$
	44	$MR = 1 + (a_0 \exp(\frac{-a_1}{RT}))t + (b_0 + b_1 \ln T)t^2$
	45	$MR = 1 + (a_0 + a_1 \ln T)t + (b_0 \exp(\frac{-b_1}{RT}))t^2$
	46	$MR = 1 + (a_0 + a_1 \ln T)t + (b_0 + b_1 \ln T)t^2$
Approximation of diffusion	47	$MR = a_0 \exp(\frac{-a_1}{RT}) \exp(-(k_0 \exp(\frac{-k_1}{RT}))t) + (1\text{-}a_0 \exp(\frac{-a_1}{RT})) \exp(-(k_0 \exp(\frac{-k_1}{RT}))b_0 \exp(\frac{-b_1}{RT})t)$
	48	$MR = (a_0 + a_1 \ln T) \exp(-(k_0 \exp(\frac{-k_1}{RT}))t) + (1\text{-}(a_0 + a_1 \ln T)) \exp(-(k_0 \exp(\frac{-k_1}{RT}))b_0 \exp(\frac{-b_1}{RT})t)$
	49	$MR = (a_0 + a_1 \ln T) \exp(-(k_0 + k_1 \ln T)t) + (1\text{-}(a_0 + a_1 \ln T)) \exp(-(k_0 + k_1 \ln T)b_0 \exp(\frac{-b_1}{RT})t)$
	50	$MR = a_0 \exp(\frac{-a_1}{RT}) \exp(-(k_0 + k_1 \ln T)t) + (1\text{-}a_0 \exp(\frac{-a_1}{RT})) \exp(-(k_0 + k_1 \ln T)b_0 \exp(\frac{-b_1}{RT})t)$
	51	$MR = a_0 \exp(\frac{-a_1}{RT}) \exp(-(k_0 \exp(\frac{-k_1}{RT}))t) + (1\text{-}a_0 \exp(\frac{-a_1}{RT})) \exp(-(k_0 \exp(\frac{-k_1}{RT}))(b_0 + b_1 \ln T)t)$
	51	$MR = (a_0 + a_1 \ln T) \exp(-(k_0 \exp(\frac{-k_1}{RT}))t) + (1\text{-}(a_0 + a_1 \ln T)) \exp(-(k_0 \exp(\frac{-k_1}{RT}))(b_0 + b_1 \ln T)t)$
	52	$MR = (a_0 + a_1 \ln T) \exp(-(k_0 + k_1 \ln T)t) + (1\text{-}(a_0 + a_1 \ln T)) \exp(-(k_0 + k_1 \ln T)(b_0 + b_1 \ln T)t)$
	53	$MR = a_0 \exp(\frac{-a_1}{RT}) \exp(-(k_0 + k_1 \ln T)t) + (1\text{-}a_0 \exp(\frac{-a_1}{RT})) \exp(-(k_0 + k_1 \ln T)(b_0 + b_1 \ln T)t)$

TABLE 2 MODELS DERIVED FROM MODELS IN TABLE 1(CONT.)

Derived	No.	Model
Midilli-Kucuk	54	$MR = a_0 \exp(\frac{-a_1}{RT}) \exp(-(k_0 \exp(\frac{-k_1}{RT}))t^{N_0 \exp(\frac{-N_1}{RT})}) + b_0 \exp(\frac{-b_1}{RT})t$
	55	$MR = (a_0 + a_1 \ln T) \exp(-(k_0 \exp(\frac{-k_1}{RT}))t^{N_0 \exp(\frac{-N_1}{RT})}) + b_0 \exp(\frac{-b_1}{RT})t$
Midilli-Kucuk	56	$MR = a_0 \exp(\frac{-a_1}{RT}) \exp(-(k_0 + k_1 \ln T)t^{N_0 \exp(\frac{-N_1}{RT})}) + b_0 \exp(\frac{-b_1}{RT})t$
	57	$MR = a_0 \exp(\frac{-a_1}{RT}) \exp(-(k_0 \exp(\frac{-k_1}{RT}))t^{(a_0 + a_1 \ln T)}) + b_0 \exp(\frac{-b_1}{RT})t$
	58	$MR = a_0 \exp(\frac{-a_1}{RT}) \exp(-(k_0 \exp(\frac{-k_1}{RT}))t^{N_0 \exp(\frac{-N_1}{RT})}) + (b_0 + b_1 \ln T)t$
	59	$MR = (a_0 + a_1 \ln T) \exp(-(k_0 + k_1 \ln T)t^{N_0 \exp(\frac{-N_1}{RT})}) + b_0 \exp(\frac{-b_1}{RT})t$
	60	$MR = (a_0 + a_1 \ln T) \exp(-(k_0 \exp(\frac{-k_1}{RT}))t^{(N_0 + N_1 \ln T)}) + b_0 \exp(\frac{-b_1}{RT})t$
	61	$MR = (a_0 + a_1 \ln T) \exp(-(k_0 \exp(\frac{-k_1}{RT}))t^{N_0 \exp(\frac{-N_1}{RT})}) + (b_0 + b_1 \ln T)t$
	62	$MR = a_0 \exp(\frac{-a_1}{RT}) \exp(-(k_0 + k_1 \ln T)t^{(N_0 + N_1 \ln T)}) + b_0 \exp(\frac{-b_1}{RT})t$
	63	$MR = a_0 \exp(\frac{-a_1}{RT}) \exp(-(k_0 + k_1 \ln T)t^{N_0 \exp(\frac{-N_1}{RT})}) + (b_0 + b_1 \ln T)t$
	64	$MR = a_0 \exp(\frac{-a_1}{RT}) \exp(-(k_0 + k_1 \ln T)t^{(N_0 + N_1 \ln T)}) + (b_0 + b_1 \ln T)t$
	65	$MR = (a_0 + a_1 \ln T) \exp(-(k_0 + k_1 \ln T)t^{N_0 \exp(\frac{-N_1}{RT})}) + (b_0 + b_1 \ln T)t$
	66	$MR = (a_0 + a_1 \ln T) \exp(-(k_0 \exp(\frac{-k_1}{RT}))t^{(N_0 + N_1 \ln T)}) + (b_0 + b_1 \ln T)t$
	67	$MR = a_0 \exp(\frac{-a_1}{RT}) \exp(-(k_0 + k_1 \ln T)t^{(N_0 + N_1 \ln T)}) + (b_0 + b_1 \ln T)t$
	68	$MR = (a_0 + a_1 \ln T) \exp(-(k_0 + k_1 \ln T)t^{(N_0 + N_1 \ln T)}) + (b_0 + b_1 \ln T)t$

3 RESULTS AND ANALYSIS

3.1 Effect of moisture content and drying time on drying rates

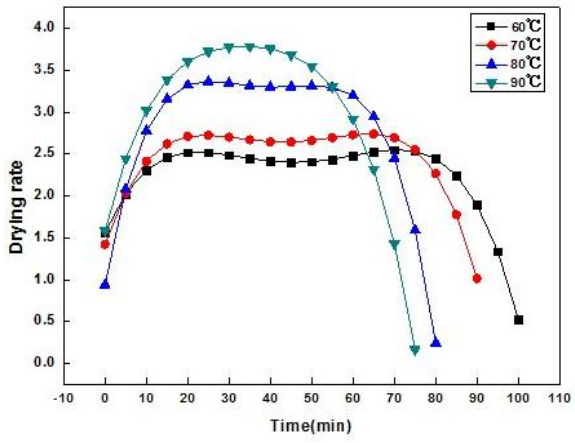


FIG.1 CURVES OF DRYING RATE VERSUS TIME

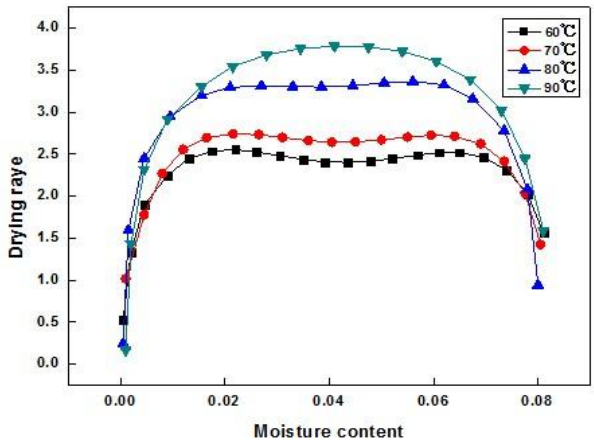


FIG.2 CURVES OF DRYING RATE VERSUS MOISTURE CONTENT

To investigate the effect of temperature on moisture content, moisture ratio, drying rate, drying time, four temperatures (60,70,80,90℃) were applied for drying of 2 ± 0.002g RDX. As the temperature was increased, the drying time of samples was decreased shown in FIG.1, as expected. The drying process reducing the moisture content of RDX from 0.08 down to 0.001 (dry base) took around 100-75 min for 60-90℃, respectively. By working at 90℃ instead of 60℃, the drying time was shortened by 25%. At any given temperature from 60 ℃ to 90 ℃, an increase of temperature leads to higher drying rate, however, at a range from 60 ℃ to 70 ℃ and from 80 ℃ to 90 ℃, there is a slower growth rate, besides, higher temperature may give rise to explosion of RDX. Therefore, the setup of temperature should not be too high. In theory, the higher the temperature is, the higher drying rate is, but the advance of drying rate at 90 ℃ is smaller in comparison with that at 80 ℃, besides, higher temperature may give rise to explosion of RDX. Therefore, the setup of temperature should not be too high.

Since the initial moisture contents of samples used in drying experiments were relatively constant (0.08), the difference in the required drying time was attributed to the disparity in drying rates given in FIG.2. As it can be seen from this figure, after a short warming-up period, a long constant rate period and a falling rate period were observed. Depending on the drying conditions, average drying rates at constant rate period ranged from 2.474 to 3.646 for the temperatures between 60 and 90℃, respectively. As the temperature was increased, the drying rate of sample was apparently increased. During the constant drying stage, the proportion of the necessary drying time varied with temperatures from 40 up to 70% for 60-90℃. The constant rate period changed nearly from 0.070 to about 0.013(dry base), nearly from 0.069 to about 0.017, nearly from 0.062 to about 0.016, nearly from 0.061 to about 0.016 as the temperature increased from 60 to 90℃ respectively. The constant rate period was followed by a falling rate period in which the moisture content would decrease to 0.01 (or below) for all drying conditions.

3.2 Modelling of drying curves

The variation of moisture ratio versus drying time is given in FIG.3 from which we concluded that moisture ratio decreased exponentially with time. Difference between moisture ratios increased gradually from the beginning of drying, which was notable between 70 and 80℃, but not conspicuous between 80 and 90℃ similar to that of between 60 and 70℃. Ten models (seen in TABLE 1) had been used to describe drying curves. The corresponding parameters of these models were presented in TABLE 3.The acceptability of the model is based on average values of regression coefficients (R) and chi-square values represented in FIG. 4, from which it can be obviously seen that, for all the tested levels, model 10 (Midilli-Kucuk) is the highlight exhibiting the lowest regression coefficient and the highest chi-square compared to those of other tested models and consequently it is chosen as the best suitable one. Analysis of the residual (MR_{exp}-MR_{pre}) for model 10 is shown in FIG.5. The residuals obtained from this model were randomly distributed and the average values of residual were close to zero in all temperatures, which also confirmed the feasibility of model 10.

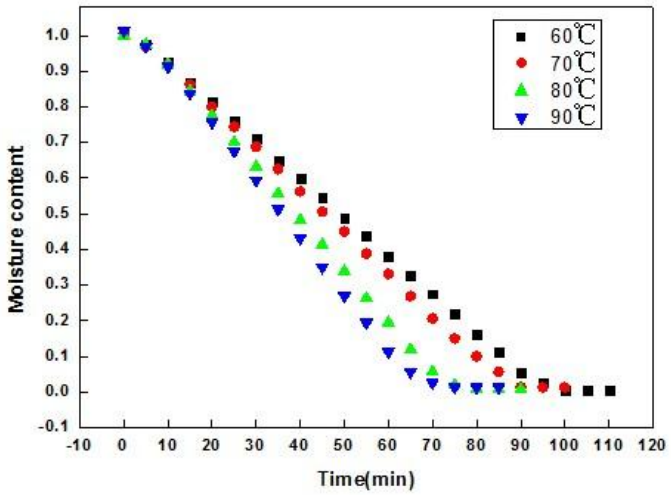


FIG.3 THE VARIATION OF MOISTURE RATIO VERSUS DRYING TIME

TABLE 3 SIMULATION RESULTS OF DRYING MODELS IN TABLE 1.

Model	T(℃)					R	chi-square
1	60	k=0.01771				0.99742	0.01106
	70	k=0.01892				0.99418	0.01987
	80	k=0.02275				0.99310	0.01312
	90	k=0.02472				0.98673	0.01309
2	60	k=0.00068	N=1.79933			0.98765	0.00137
	70	k=0.00077	N=1,80109			0.98748	0.00119
	80	k=0.00068	N=1.91340			0.98915	0.00105
	90	k=0.00074	N=1.93043			0.99604	0.00075
3	60	a=1.14944	k=0.02042			0.99630	0.00824
	70	a=1.14411	k=0.02175			0.99193	0.00819
	80	a=1.15954	k=0.02629			0.99001	0.00995
	90	a=1.16557	k=0.02866			0.98882	0.00965
4	60	k=0.01739	N=1.79932			0.98969	0.00137
	70	k=0.01871	N=1.80109			0.98980	0.00119
	80	k=0.02208	N=0.91339			0.99141	0.00105
	90	k=0.02392	N=1.93042			0.99861	0.00075
5	60	a=3.01863	k=0.00417	c=-1.97192		0.99893	0.00071
	70	a=3.39289	k=0.00391	c=-2.34950		0.99842	0.00067
	80	a=2.43527	k=0.00705	c=-1.36994		0.99855	0.00171
	90	a=2.07519	k=0.00953	c=-0.99642		0.95189	0.00211
6	60	a=4.40038	k=0.00352	b=-3.35316	k0=0.00086	0.95221	0.00075
	70	a=4.96213	k=0.00330	b=-3.91827	k0=0.00079	0.99742	0.00071
	80	a=5.13918	k=0.00524	b=-4.07294	k0=0.00240	0.99418	0.00179
	90	a=5.39369	k=0.00673	b=-4.31393	k0=0.00383	0.99310	0.00221
7	60	a=2.09922	k=0.02952			0.98673	0.00325
	70	a=2.10170	k=0.03173			0.98765	0.00301
	80	a=2.15934	k=0.03860			0.98748	0.00339
	90	a=2.17322	k=0.04206			0.98915	0.00303
8	60	a=-0.01086	b=0.00001			0.99604	0.00097
	70	a=-0.01152	b=0.00001			0.99630	0.00090
	80	a=-0.01417	b=0.00002			0.99193	0.00217
	90	a=-0.01583	b=0.00004			0.99001	0.00279
9	60	a=957.00383	k=0.04010	b=1.00117		0.98882	0.00288
	70	a=954.61483	k=0.04314	b=1.00117		0.98969	0.00265
	80	a=1028.87513	k=0.05297	b=1.00117		0.98980	0.00294
	90	a=1011.46334	k=0.05786	b=1.00121		0.99141	0.00256
10	60	a=0.99444	k=0.00145	N=1.52599	b=-0.00171	0.99861	0.00038
	70	a=0.99211	k=0.00147	N=1.55135	b=-0.00181	0.99893	0.00029
	80	a=0.98549	k=0.00092	N=1.78181	b=-0.00102	0.99842	0.00049
	90	a=0.98916	k=0.00093	N=1.83754	b=-0.00070	0.99855	0.00046

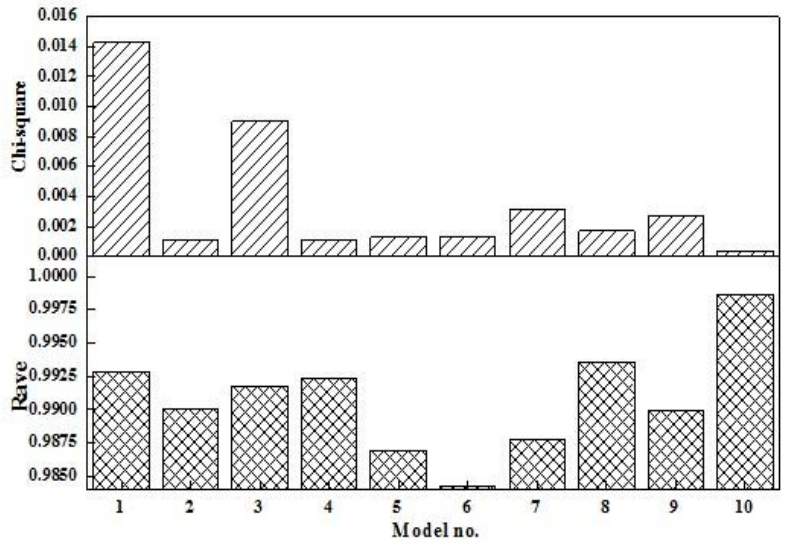


FIG. 4. AVERAGE REGRESSION COEFFICIENT AND CHI-SQUARE VALUES OF MODELS IN TABLE 3.

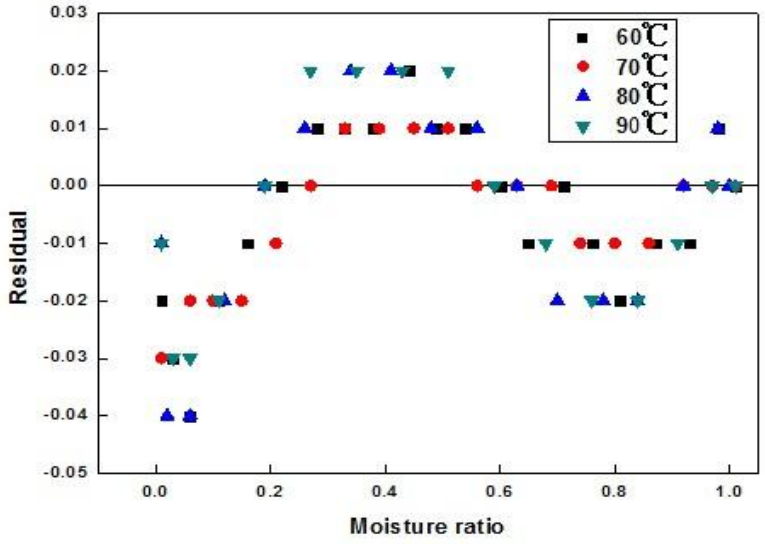


FIG. 5. RESIDUAL PLOT OF MIDILLI-KUCUK EQUATION

It should be noted that the constants in TABLE 3 are available only to the range of drying temperatures and drying time in this study. Model 10 will be applicable for the energetic material related with RDX. Further study is anticipated for other drying temperatures, drying time and other research objects.

Drying temperature is also an essential factor effecting moisture ratio besides drying time, and models in TABLE 1 as well as previous researches in the field of drying involve little combination effect of drying temperatures and drying time, which is the deficiency in this work and others in the literature. Furthermore, correlating discussion indicated temperature had the foremost effect on drying process of RDX among all the other drying influencing factors mainly involving vacuum, initial moisture content, and thus, without regard to these subordinate drying influencing parameters, Arrhenius type and Logarithmic type merely concerning drying temperature were brought into the constants or coefficients of the models in TABLE 1. By means of different combination of these functions, 2n new model derived from each model in TABLE 1 was summarized in TABLE 2. The values of statistical analysis were given in TABLE 4.

TABLE 4 SIMULATION RESULTS OF DRYING MODELS IN TABLE 2.

Model	R	MBE	RMSE	$\chi 2$	EF
1	0.949737	-0.00836	0.10255	0.010813	0.901675
2	0.94921	-0.00781	0.102923	0.010892	0.900958
3	0.994987	0.008493	0.033352	0.001177	0.989600
4	0.993982	0.008767	0.033104	0.001159	0.989754
5	0.993982	0.008767	0.033104	0.001159	0.989754
6	0. 993982	0.008767	0.033104	0.001159	0.989754
7	0.964365	0.01274	0.086697	0.007952	0.929725
8	0.964365	0.01274	0.086697	0.007952	0.929725
9	0.964365	0.01274	0.086697	0.007952	0.929725
10	0.964365	0.01274	0.08669	0.007952	0.929736
11	0.994987	0.008219	0.03331	0.001174	0.989626
12	0.975326	0.007534	0.05428	0.005381	0.972453
13	0.994987	0.008219	0.03331	0.001174	0.989626
14	0.965919	-0.02781	0.085215	0.007683	0.932107
15	0.997497	0.000137	0.022905	0.000572	0.995095
16	0.997497	-0.00041	0.022725	0.000563	0.995172
17	0.997497	0	0.022935	0.000573	0.995082
18	0.997497	-0.00027	0.022995	0.000576	0.995056
19	0.997497	-0.00027	0.023054	0.000579	0.995031
20	0.997497	0.000548	0.023173	0.000585	0.994979
21	0.997497	0.000137	0.023203	0.000587	0.994966
22	0.997497	0.000548	0.023054	0.000579	0.995031
23	0.997998	0.000548	0.021708	0.000529	0.995594
24	0.997998	0	0.022269	0.000557	0.995363
25	0.997998	0.000548	0.021518	0.00052	0.995671
26	0.997998	0	0.022391	0.000563	0.995313

TABLE 4 SIMULATION RESULTS OF DRYING MODELS IN TABLE 2. (CONT.)

Model	R	MBE	RMSE	χ2	EF
27	0.997998	-0.00014	0.022299	0.000558	0.995351
28	0.997998	0	0.021959	0.000542	0.995492
29	0.997998	-0.00014	0.021802	0.000534	0.995556
30	0.997998	0.000274	0.022083	0.000548	0.995441
31	0.997998	-0.00027	0.022021	0.000545	0.995466
32	0.997998	-0.00014	0.022052	0.000546	0.995453
33	0.997998	0	0.022452	0.000566	0.995287
34	0.997497	0	0.022269	0.000557	0.995364
35	0.997998	0.000274	0.020806	0.000486	0.995953
36	0.997998	-0.00027	0.022021	0.000545	0.995466
37	0.997998	-0.00041	0.021676	0.000528	0.995607
38	0.997998	-0.00055	0.021645	0.000526	0.995620
39	0.987421	0.010685	0.051151	0.002768	0.975537
40	0.949737	-0.00781	0.102563	0.011129	0.901650
41	0.987421	0.010274	0.05103	0.002755	0.975653
42	0.996494	-0.00644	0.027623	0.000807	0.992866
43	0.996494	-0.00534	0.026354	0.000735	0.993506
44	0.995992	-0.00507	0.026197	0.000726	0.993584
45	0.996494	-0.00534	0.026664	0.000752	0.993353
46	0.995992	-0.00466	0.02638	0.000736	0.993494
47	0.989444	0.009863	0.047079	0.002415	0.979277
48	0.989444	0.009863	0.047079	0.002415	0.979277
49	0.989444	0.010959	0.047108	0.002418	0.979252
50	0.989444	0.009863	0.046435	0.002349	0.979840
51	0.989444	0.009863	0.047079	0.002415	0.979277
52	0.989444	0.009589	0.047456	0.002454	0.978944
53	0.989444	0.009589	0.047456	0.002454	0.978944
54	0.989444	0.00027	0.047657	0.002551	0.978765
55	0.989444	0.00041	0.047672	0.002552	0.978752
56	0.997497	-0.000548	0.022391	0.000563	0.995312
57	0.997497	0	0.021834	0.000535	0.995543
58	0.997497	0.00014	0.022422	0.000565	0.995300
59	0.997497	-0.000411	0.022052	0.000546	0.995453
60	0.997497	-0.000137	0.023261	0.000608	0.994941
61	0.997497	0	0.022513	0.000569	0.995261
62	0.992975	-0.000137	0.039012	0.001709	0.985771
63	0.997497	0.00014	0.022483	0.000568	0.995274
64	0.997497	0.00014	0.022483	0.000568	0.995274
65	0.997497	0.000274	0.023114	0.0006	0.995005
66	0.997497	0.00014	0.022483	0.000568	0.995274
67	0.997497	0.00014	0.022483	0.000568	0.995274
68	0.997497	-0.000411	0.021928	0.00054	0.995504

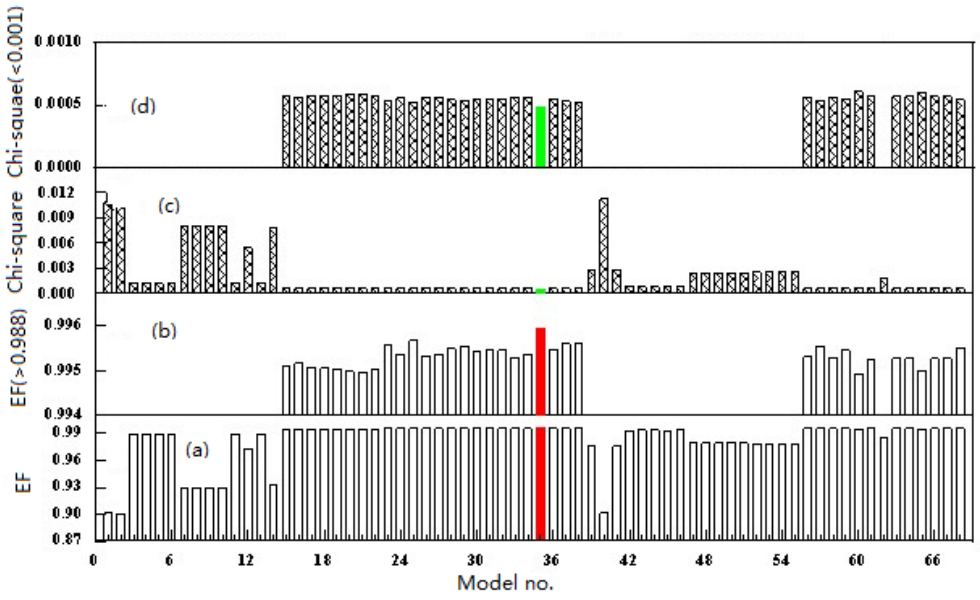
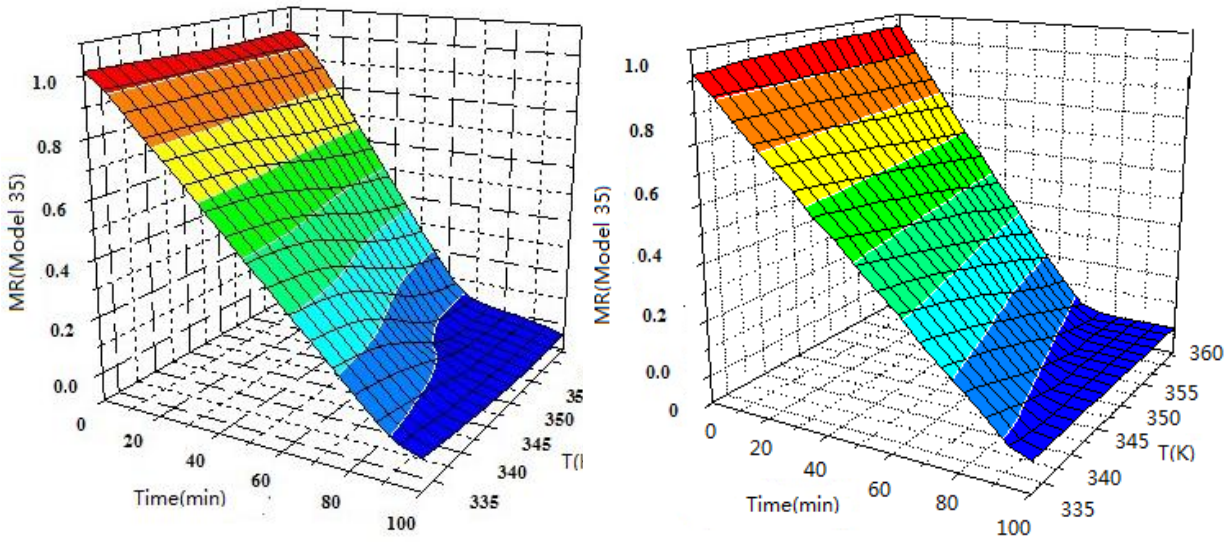


FIG. 6 EF AND CHI-SQUARE VALUES OF MODEL

EF (FIG.6(a)) and chi-square (FIG.6(c)) values of 68 models in Table 4, the model qualifying R values greater than 0.994 (FIG.6(b)) and having chi-square values lower than 0.001 (FIG.6(d)) were represented with bars in FIG.6 from

which it can be directly seen that, the modelling efficiency of all the 68 models was approximately favorable for modelling of drying curves of RDX, besides, the models 15-22 derived from Logarithmic, 23-28 from Two term model, 56-61 and 62-68 from the indicated greater modelling efficiency available with higher *EF* values and lower chi-square values than that in the other models. In addition, model 35 exhibited the highest *R*, *EF* values and lowest chi-square value (seen from TABLE 4 and FIG.6), and hence, it was recommended to describe the static drying of RDX. The following function (model 35) was proposed to evaluate the moisture ratio of RDX versus drying time and temperature selected.

MR=(-0.921)*EXP(4101.105/(8.314*T))*EXP(-((-2.583E-9)*EXP(35846.457/(8.314*T)))*t)+1.708*EXP(-(-3013.100)/(8.314*T))*EXP(-((-0.137)+0.024*LN(T))*t)



(a) TESTED SURFACE (b) SIMULATED SURFACE

FIG. 7 VARIATION OF MOISTURE RATIO TESTED AND SIMULATED BY MODEL 35 VERSUS DRYING TIME AND TEMPERATURE, RESPECTIVELY.

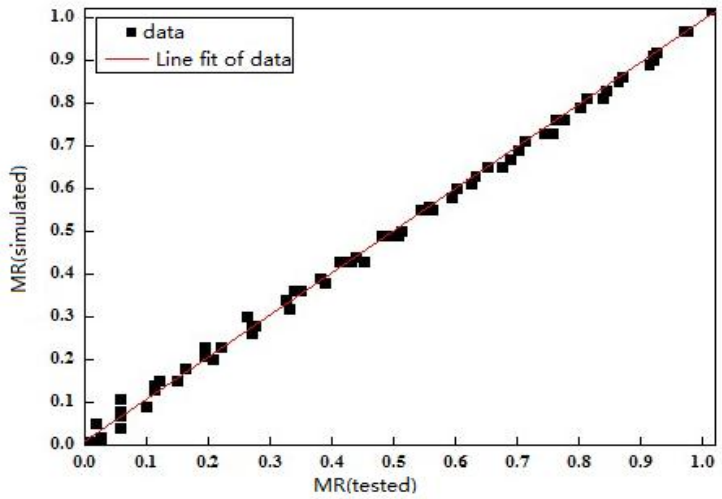


FIG. 8 TESTED MOISTURE RATIO AND SIMULATED MOISTURE RATIO BY MODEL 35 OF RDX, RESPECTIVELY.

4 CONCLUSIONS

This work indicated that the drying time of RDX decreased and the drying rate increased as the applied temperature increased; and a prolonged constant rate period was observed followed by a falling rate period after a short accelerating period at the beginning of the drying process of RDX, which nearly took 40-70% of the total drying time for 60-90℃, respectively, consuming most of drying time in comparison with the accelerating period and the falling rate period.

In order to estimate and select the suitable form of RDX drying curves, 10 different drying models in the literature and 68 new derived models were applied to the experimental data and compared according to their coefficients of determination , which were predicted by non-linear regression analysis using the Statistical routine. It was deduced that the model 35 derived from Two term model could sufficiently describe the drying behavior of RDX at a temperature range of 60-90℃, giving a R of 0.997998, MBE of 0.000274, RMSE of 0.020806, χ^2 of 0.000486 and EF of 0.995953. The proposed models depicted an excellent fit and would be helpful in the industrial application concerning RDX, providing important references for production practices.

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