https://doi.org/10.31891/2307-5732-2026-363-47
УДК 681.5.015

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СТРУКТУРНА ТА ПАРАМЕТРИЧНА ІДЕНТИФІКАЦІЯ ЗЕРНОСУШАРКИ З ТЕПЛОВИМ НАСОСОМ ЯК ОБ'ЄКТУ КЕРУВАННЯ

Енергоефективність зерносушильних систем набуває особливої актуальності через високі енергетичні витрати під час сушіння зерна, зокрема насіннєвого, а також у зв'язку зі зростанням вартості енергоносіїв. Теплонасосне сушіння розглядається як перспективна технологія, однак для забезпечення оптимального співвідношення між енергоефективністю та технічними можливостями обладнання необхідне подальше вдосконалення систем керування. Аналіз літературних джерел показав, що в наявних дослідженнях теплонасосного сушіння аграрної продукції недостатньо уваги приділено вивченню взаємодії основних параметрів процесу, впливу зовнішніх збурень та динамічних властивостей теплового насоса і сушильної камери. У цій роботі запропоновано підхід до розв'язання зазначеної проблеми шляхом проведення структурної та параметричної ідентифікації зерносушарки як об'єкта керування. Для цього розроблено технологічну схему процесу теплонасосного сушіння насіння ріпаку на базі модернізованої зерносушарки неперервної дії французького виробництва. Проведено експериментальне дослідження параметрів процесу сушіння. Визначений взаємний вплив основних параметрів процесу: температури та вологовмісту сушильного агенту, температури та вологості насіння, а також початкових умов. На основі експериментальних даних отримано статичні та динамічні характеристики каналів керування «вологовміст сушильного агенту – вологість насіння» та «температура сушильного агенту – температура насіння». Показано, що обидва канали мають практично лінійні залежності в робочому діапазоні контрольованих параметрів, проте спостерігається суттєвий перехресний вплив, особливо з боку температури сушильного агенту. Встановлено, що початкова вологість насіння є значущим контрольованим збуренням, яке впливає як на тривалість сушіння, так і на кінцеву температуру продукту. На основі аналізу побудовано узагальнену параметричну схему зерносушарки з тепловим насосом, що включає основні канали керування, перехресні зв'язки та збурення. Отримані результати створюють підґрунтя для подальшої розробки імітаційної моделі та синтезу ефективних алгоритмів автоматичного керування процесом теплонасосного сушіння.

Ключові слова: *зерносушарка, тепловий насос, статичні характеристики, динамічні характеристики, ідентифікація параметрів.*

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STRUCTURAL AND PARAMETRIC IDENTIFICATION OF THE GRAIN DRYER WITH HEAT PUMP AS A CONTROL OBJECT

Energy efficiency of grain drying systems is becoming particularly relevant due to the high energy costs during grain drying, in particular seed grain drying, as well as due to the increasing cost of energy carriers. Heat pump drying is considered a promising technology, however, to ensure the optimal ratio between energy efficiency and technical capabilities of the equipment, further improvement of control systems is necessary. An analysis of the literature showed that in existing studies of heat pump drying of agricultural products, insufficient attention is paid to studying the interaction of the main process parameters, the influence of external disturbances, and the dynamic properties of the heat pump and the drying chamber. This paper proposes an approach to solving the specified problem by conducting structural and parametric identification of the grain dryer as a control object. For this purpose, a technological diagram of the rapeseed heat pump drying process was developed based on a modernized continuous-flow grain dryer of French production. An experimental study of the drying process parameters was conducted. The mutual influence of the main process parameters was determined: the drying agent temperature and moisture content, the seeds temperature and humidity, as well as the initial conditions. Based on the experimental data, the static and dynamic characteristics of the control channels "drying agent moisture content - seed humidity" and "drying agent temperature - seed temperature" were obtained. It was shown that both channels have practically linear dependencies in the operating range of the controlled parameters, however, a significant cross-coupling effect is observed, especially from the side of the drying agent temperature. It was established that the initial seed humidity is a significant controlled disturbance that affects both the drying duration and the final temperature of the product. Based on the analysis, a generalized parametric diagram of the grain dryer with the heat pump was constructed, which includes the main control channels, cross-connections and disturbances. The obtained results create a basis for further development of a simulation model and synthesis of effective algorithms for automatic control of the heat pump drying process.

Keywords: *grain dryer, heat pump, static characteristics, dynamic characteristics, parameter identification.*

Стаття надійшла до редакції / Received 18.01.2026
Прийнята до друку / Accepted 11.02.2026
Опубліковано / Published 26.03.2026

Problem statement

At present, both in Ukraine and worldwide, there is an acute need for the design and development of highly efficient grain drying equipment that enables the minimization of energy consumption while ensuring high seed germination capacity. To remove 70-80 kg of moisture from one ton of grain, a significant amount of energy is required on average; for a total harvest of 35-40 million tons, this corresponds to 0.4-0.7 million tons of conventional fuel [1]. For seed grain drying, heat consumption is approximately 30% higher than for food or technical grain, which is due to stricter requirements for seed quality. Energy-saving issues become even more critical against the background of rising energy prices.

One of the promising approaches is the application of heat pump drying (HPD) [2], which contributes to the development of energy-efficient and environmentally safe technological units for grain processing. However, the operational constraints imposed on such technological units as the drying chamber (DC) and the heat pump (HP) come into conflict with their optimal operating modes.

To resolve this contradiction, improvement of drying process control algorithms is possible; however, this cannot be achieved without prior structural and parametric identification of the main process channels. The application of advanced control algorithms makes it possible to find a compromise between energy efficiency and the technical capabilities of grain HPD systems.

Thus, the development of the structure and parameter identification of a grain dryer with a heat pump as a control object constitutes a relevant scientific and technical problem.

Literature review

A large number of studies are devoted to HPD. In works [3, 4], the processes of drying agricultural products in heat pump dryers are investigated, and evaluations of key performance indicators are carried out, including energy efficiency, effects on product color and composition, as well as techno-economic, exergo-economic, and environmental indicators. These studies confirm high values of the coefficient of energy efficiency (CEE) of up to 5.338 and the specific moisture removal rate (SMRR) of up to 9.25 kg/kWh, as well as a significant reduction in energy consumption of up to 80% when using heat pumps compared to conventional drying methods.

In [5, 6], an analysis of the energy efficiency of heat pump drying machines is performed, along with a comprehensive comparison of various auxiliary HPD systems, such as infrared, ultrasonic, and solar-assisted technologies. It is reported that the CEE for HPD ranges from 3.5 to 4.5, the SMRR varies from 0.8 to 1.2 kg/kWh, and the specific energy consumption for moisture evaporation is 0.5–0.7 kWh/kg, which indicates a significant improvement compared to traditional drying methods. It is also established that the use of solar energy in combination with HPD improves thermal energy utilization efficiency by 86.6% and reduces drying time and energy consumption by 18.5% and 26.2%, respectively. These studies highlight the energy-saving potential and enhanced performance of HPD technology.

To confirm the effectiveness of HPD, many authors [4, 7–12] have carried out structural and parametric identification as well as modeling of operating modes of heat pump dryers. In particular, works [7, 8] present a thermodynamic analysis of heat pump operation as part of a dryer and determine efficiency indicators such as CEE and SMRR. In addition, expressions for the main drying process parameters are provided, including drying agent (DA) temperature, moisture content, and flow rate, compressor pressure difference, drying load, evaporator cooling capacity, and condenser heating capacity. It is noted that these parameters are often interrelated through nonlinear dependencies.

The authors of studies [4, 9, 10] propose the use of kinetic models to investigate drying processes of agricultural products. The main drawback of such models is their lack of universality. The performance of kinetic models depends on a large number of parameters, including constant empirical coefficients. In general, such models are applied only for approximate statistical estimation of drying process parameters and cannot be used for the synthesis of control algorithms.

In [11], identification of kinetic indicators and efficiency parameters of the apple drying process is carried out. Based on the obtained data, the authors propose a mathematical model for drying process analysis, formulated using partial differential equations describing diffusion–filtration heat and mass transfer, phase transformations, and shrinkage during the drying of colloidal capillary-porous materials. The application of such nonlinear equations significantly complicates the development of control algorithms and the implementation of the model in widely used software environments.

In [12], a relatively simple dynamic model of the HPD process with identification of the main drying parameters is proposed. Despite the effectiveness of this model, it describes only the processes occurring within the DC and does not take into account the dynamic characteristics of the HP, nor the influence of external uncontrolled disturbances.

Summarizing the presented review, it can be concluded that insufficient attention has been paid to accounting for the cross-coupling effects of the main parameters of both the DC and the HP, the influence of external disturbances, and the possibilities for linearization of the mathematical model equations in studies of HPD of agricultural products. To address this problem, the present work proposes structural and parametric identification of the main HPD process channels using experimental data obtained from an SBC-type continuous-flow grain dryer equipped with HP manufactured in France.

Purpose of the article

The purpose of this study is to perform structural and parametric identification and to develop models of the main control channels, cross-coupling links, and controlled disturbances of the grain HPD process. These models will serve as a basis for the development of a simulation model of a grain dryer with a HP as a control object and for the synthesis of effective control algorithms for the HPD process.

To achieve the stated purpose, the following tasks are addressed in this work:

1. To obtain static and dynamic relationships of the main drying process parameters based on experimental data.
2. To develop a structural and parametric diagram of a grain dryer with a HP as a control object.
3. To perform parametric identification of models of the main control channels, cross-coupling links, and controlled disturbances of the HPD process.

Materials and methods

The experiments were conducted on rapeseed in the SBC-type modified continuous-flow grain dryer equipped with an HP manufactured in France [13], located in the village of Biloziria, Cherkasy region, Ukraine. The technological diagram of the rapeseed HPD process is shown in Fig. 1.

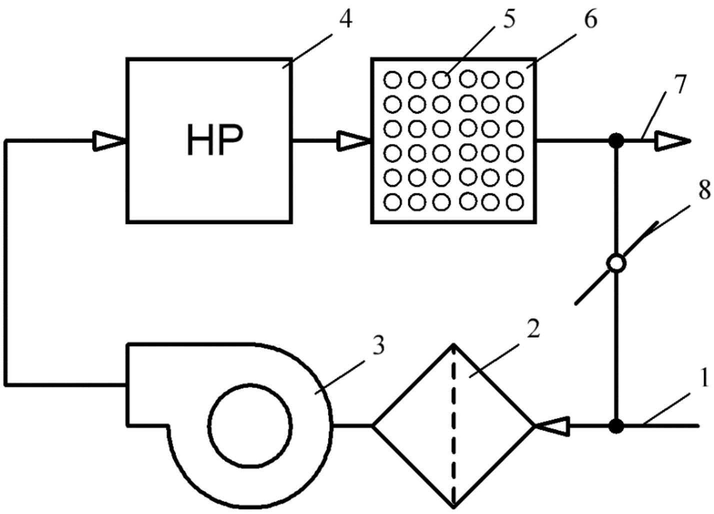


Fig. 1. Technological diagram of the rapeseed heat pump drying process

The system operates as follows. Ambient air (1) is mixed with exhaust air supplied from the DC (6) through damper (8). The resulting DA passes through a mechanical filter (2) and is delivered by a circulating fan (3) to the HP (4). After the HP, the DA with specified temperature and moisture content is supplied to the DC (6), where the rapeseed drying process (5) takes place.

Based on the technological diagram presented above, the structure of the grain dryer as a control object can be divided into two interconnected subsystems: the HP (14), where the DA conditioning process is performed, and the DC (7), where the thermal and moisture parameters of rapeseed are established. It should be noted that in [14], parametric identification was carried out and a parametric diagram of the HP as part of a continuous-flow grain dryer was presented. As a result of the conducted studies, two control channels of the DA thermal and moisture parameters were identified: temperature T_{a2} and moisture content w_{a2} (Fig. 2). The control inputs were defined as the position of the thermostatic expansion valve N_s and the rotational speed of the compressor motor n_{com}, respectively. The controlled disturbances were defined as the initial DA temperature T_{a1} and the initial DA moisture content w_{a1}, respectively.

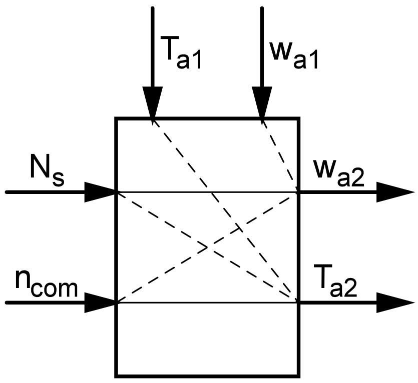


Fig. 2. Parametric diagram of the HP as part of the grain dryer

In the present study, structural and parametric identification of the DC, which constitutes the second subsystem of the grain dryer, is considered. For this purpose, it is necessary to determine the mutual influence of the main parameters of the seed drying process through experimental investigation. The main quality indicator of the drying process is the final humidity of the product, namely rapeseed. Since, according to technological requirements [1], the drying process continues until the specified seed moisture level is achieved, drying kinetics characterized by the drying time can be considered an appropriate quality indicator. In addition, according to DSTU 4138-2002 [15], rather strict requirements are imposed on the temperature regime of the drying process in order to preserve seed quality and prevent overheating.

Thus, the following scientific hypothesis can be formulated. For efficient operation of the DC, at least two control loops should be provided: rapeseed humidity and rapeseed temperature control. The control action of the seed humidity control loop is the DA moisture content w_{a2} supplied from the HP to the DC. In turn, the control action of the seed temperature control loop is the DA temperature T_{a2}.

Taking into account the above considerations and in accordance with the technological diagram (Fig. 1), the experimental part of the study was conducted using the following procedure. First, the initial rapeseed humidity was determined in accordance with DSTU [15]. Then, the seeds were loaded into the DC, where the specified drying process parameters were set and recorded: DA temperature and moisture content, seed temperature and humidity, drying time, as well as HP parameters, including the evaporation and condensation temperatures of the refrigerant. The drying process was carried out until the rapeseed humidity reached a level of 8%, after which the experimental results were processed. Subsequently, the dried seeds were unloaded from the DC, a new batch of rapeseed was loaded, different drying process parameters were set, and the experiment was repeated.

Results and discussion

The static characteristics of the DC via the seed humidity channel are shown in Fig.3.

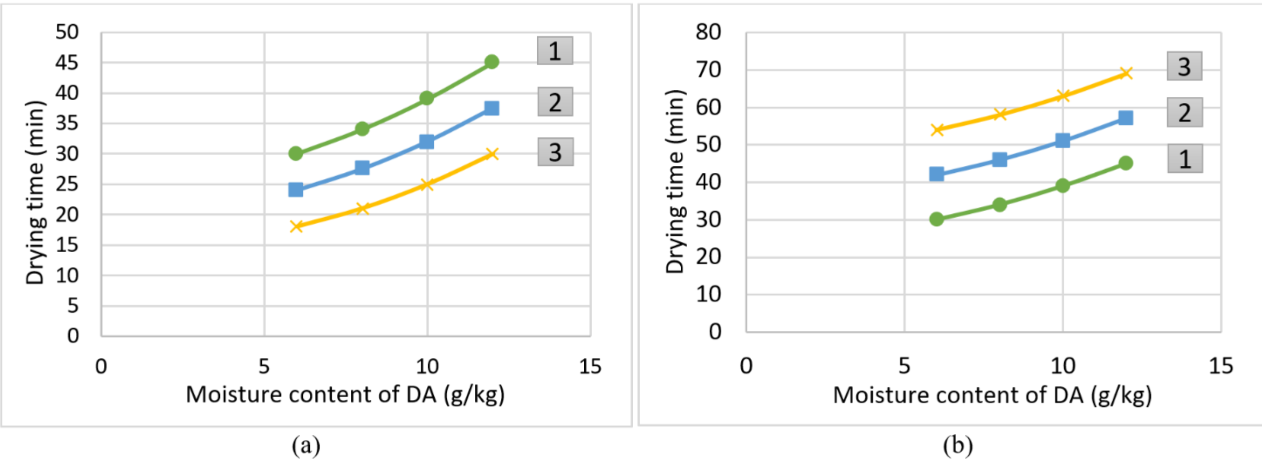


Fig. 3. Static characteristics of a DC via the seed humidity control channel

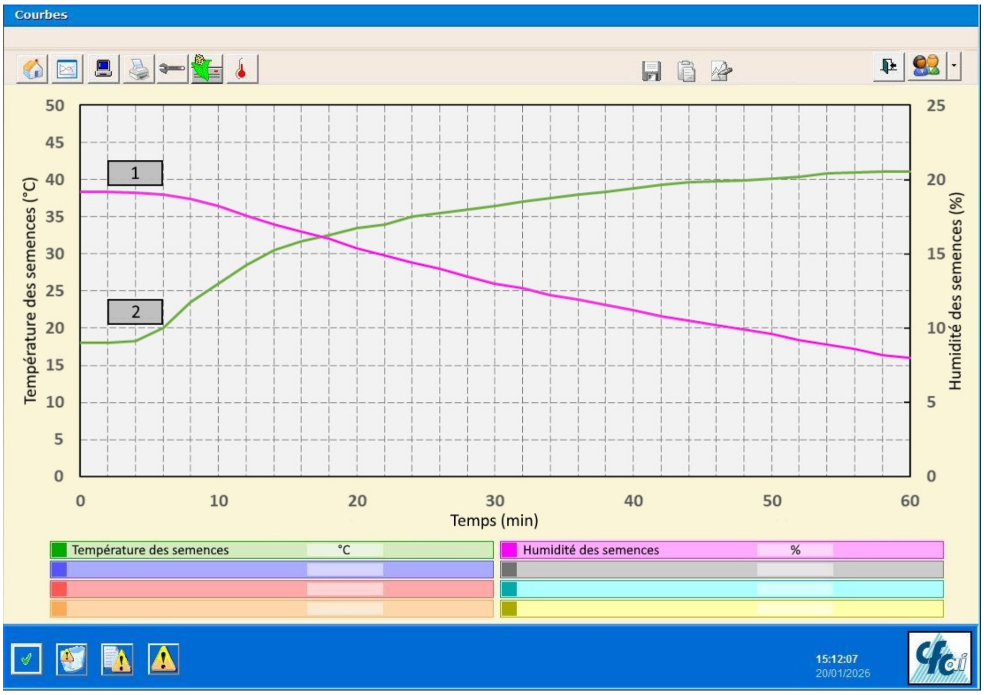
Fig. 3a presents the static dependences of the rapeseed drying process time on the DA moisture content, with an initial seed humidity of 12%, for three values of the DA temperature supplied to the DC: 1 – 50 °C; 2 – 65 °C; 3 - 80 °C. From these characteristics, it can be seen that the intensity of the drying process depends almost linearly on the DA moisture content. Fig. 3b shows the dependences of the rapeseed drying time on the DA moisture content for three values of the initial seed humidity loaded into the DC: 1 – 12%; 2 – 17%; 3 – 22%, and at a constant DA temperature of 50 °C. These dependences are also linear within the operating range of DA moisture content values.

Fig. 4a presents the time characteristics: 1 – seed humidity, %; 2 – seed temperature, °C, as the system response to the supply of a DA with a temperature of 45 °C and a moisture content of 6 g/kg at time t = 0 min, with an initial seed humidity of 19.2%. From the obtained time characteristics, it can be seen that during the transient process the seed humidity gradually decreased and reached 8% after 54 min. At the same time, the seed temperature gradually increased and reached a value of 41.1 °C after 52 °C min.

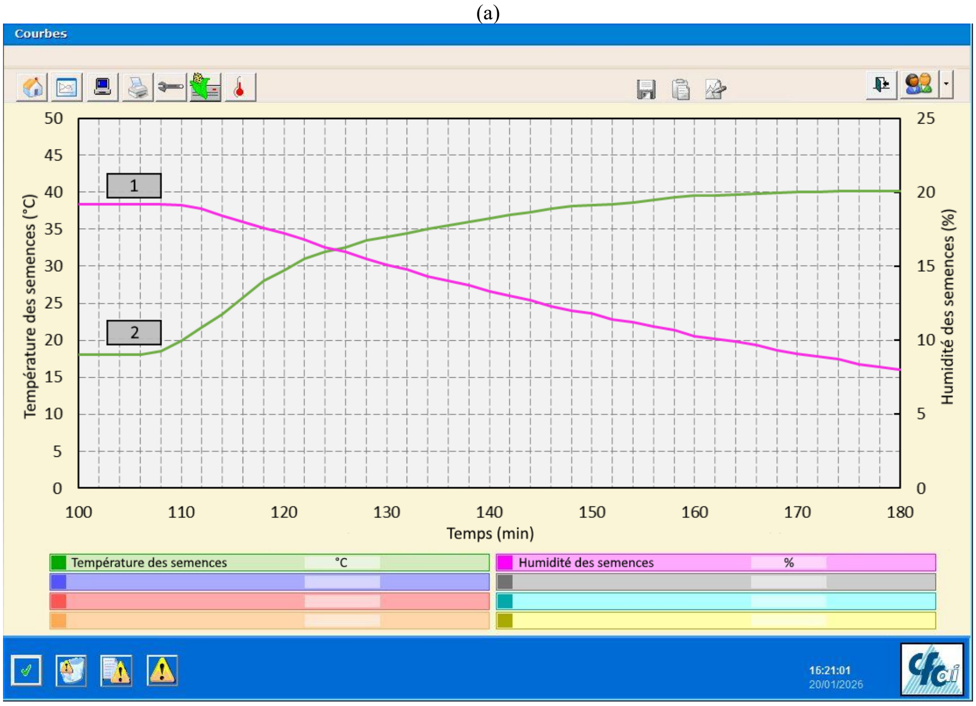
Fig. 4b presents similar time characteristics when supplying the DA with a temperature of 45 °C and a moisture content of 12 g/kg at time t = 105 min, for the same value of the initial seed humidity. The obtained time characteristics indicate the same nature of the transient process as in the previous experiment. The duration of the transient process was 70 min. The new steady-state value of the rapeseed temperature was 40.2 °C.

The static characteristics of the DC via the seed temperature control channel are shown in Fig. 5.

Fig. 5a presents the static dependences of the final rapeseed temperature on the DA temperature, with an initial seed humidity of 12%, for three values of the DA moisture content supplied to the DC: 1 – 6 g/kg; 2 – 8 g/kg; 3 - 10 g/kg. From these characteristics, it can be seen that the final rapeseed temperature depends almost linearly on the DA temperature. Fig. 5b shows the dependences of the final rapeseed temperature on the DA temperature for three values of the initial seed humidity: 1 – 12%; 2 – 19%; 3 – 32%, and at a constant DA moisture content of 10 g/kg. These dependences are also practically linear within the operating range of DA temperature values.

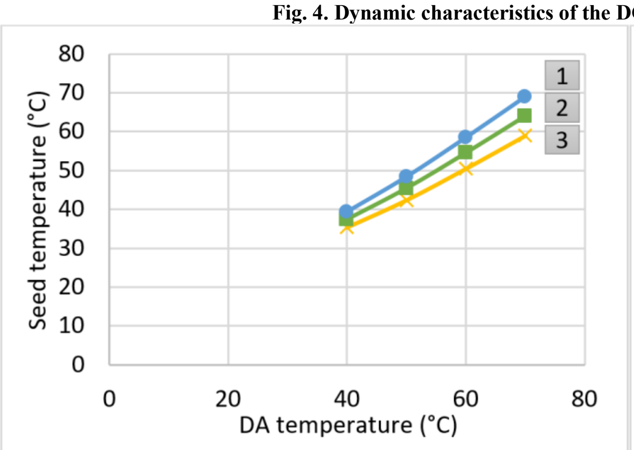


(a)

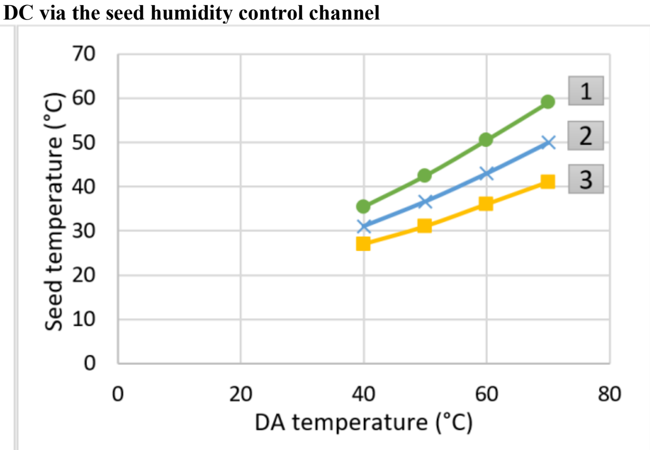


(b)

Fig. 4. Dynamic characteristics of the DC via the seed humidity control channel



(a)

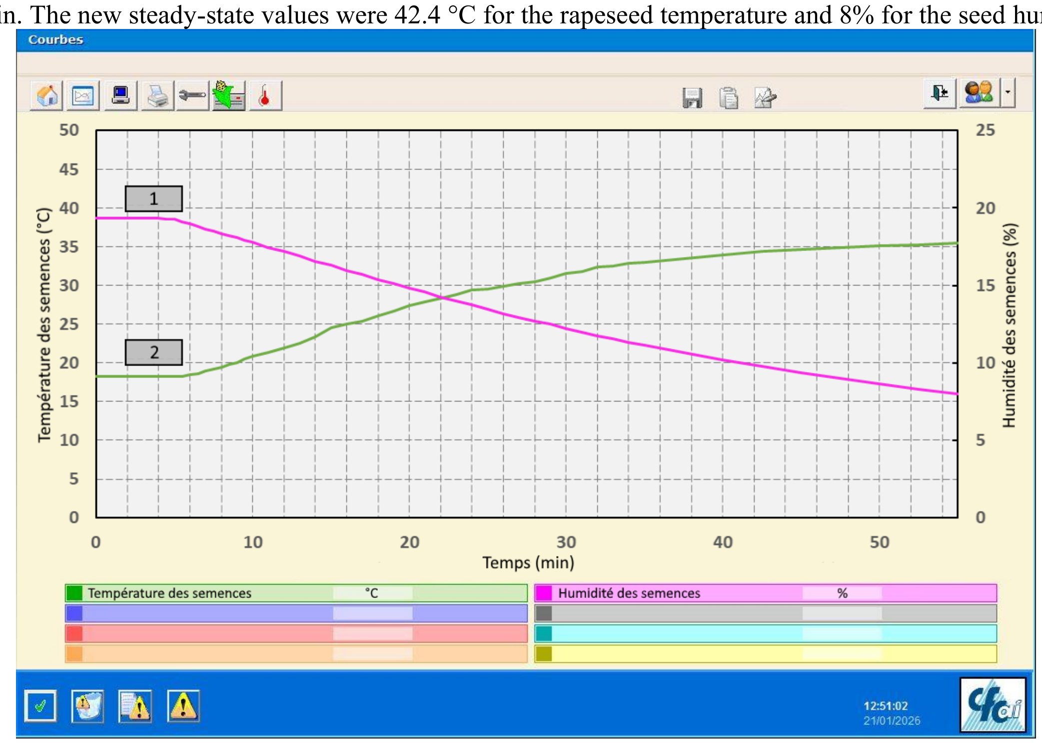


(b)

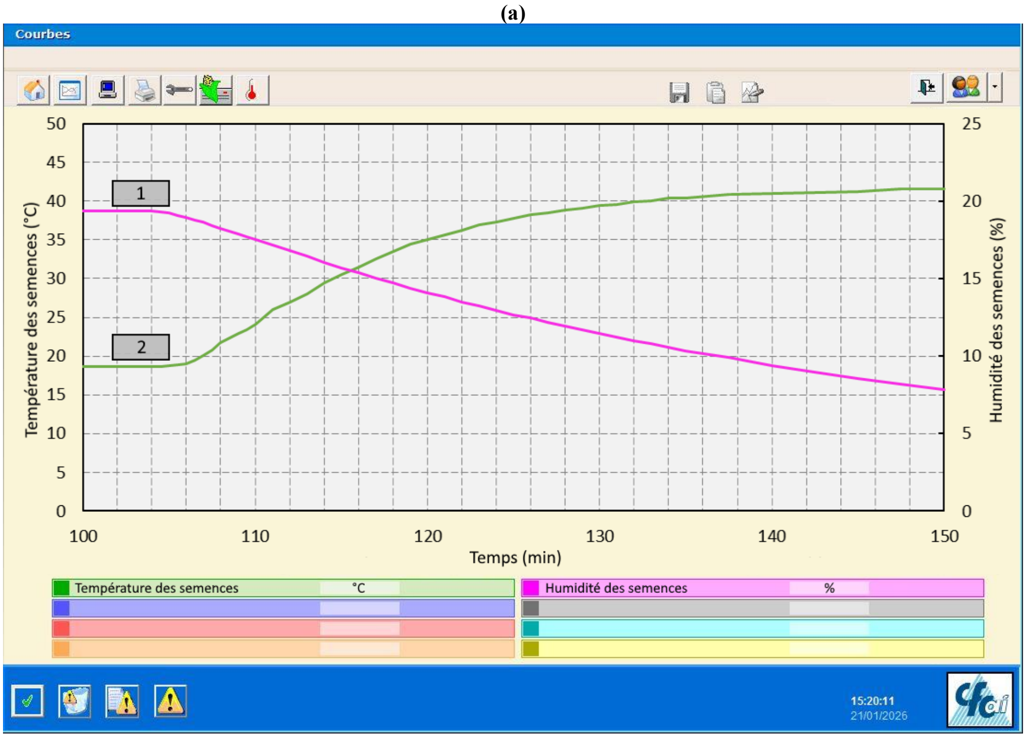
Fig. 5. Static characteristics of the DC via the seed temperature control channel

Fig. 6a presents the time characteristics: 1 – seed humidity, %; 2 – seed temperature, °C, as the system response to the supply of a DA with a temperature of 40 °C and a moisture content of 6 g/kg at time t = 2 min, with an initial seed humidity of 19.2%. From the obtained time characteristics, it can be seen that during the transient process the seed temperature gradually increased and reached 35.4 °C after 53 min. At the same time, the seed humidity gradually decreased and reached a value of 7.8% after 53 min.

Fig. 6b presents similar time characteristics when supplying the DA with a temperature of 50 °C and a moisture content of 6 g/kg at time t = 102 min, for the same value of the initial seed humidity. The obtained time characteristics indicate the same nature of the transient process as in the previous experiment. The duration of the transient process was 48 min. The new steady-state values were 42.4 °C for the rapeseed temperature and 8% for the seed humidity.



(a)



(b)

Fig. 6. Dynamic characteristics of the drying camera via the seed temperature control channel

Analysis of the static and dynamic characteristics indicates an almost linear dependence of rapeseed temperature and drying time on the thermal and moisture parameters of the DA. This confirms the scientific hypothesis formulated at the beginning of the article and makes it possible to identify two main control channels:

1. DA moisture content – seed humidity;
2. DA temperature – seed temperature.

The drying time and the rapeseed temperature after completion of the drying process significantly depend on the initial seed humidity loaded into the DC. As shown in Fig. 3b, a change in the initial seed humidity by 5% results in an increase in drying time by 12 min. At the same time, the initial seed humidity also has a significant effect (by 15%) on the final seed temperature, as shown in Fig. 5b. This dependence indicates a sufficiently strong disturbance effect acting through both control channels: rapeseed temperature and rapeseed humidity.

Analysis of the static characteristics in Fig. 3b and Fig. 5a, as well as the dynamic characteristics in Fig. 4, shows that the control action represented by the DA moisture content has a significant effect on the seed drying time; however, a much weaker effect on the steady-state rapeseed temperature is observed. On the other hand, the second control action the DA temperature demonstrates a significant influence on both controlled variables, as evidenced by the characteristics in Fig. 3a, Fig. 5b, and Fig. 6. This leads to the presence of a strong cross-coupling link in the channel "DA temperature – seed humidity" and a weak cross-coupling link in the channel "DA moisture content – seed temperature".

The conducted analysis, taking into account the results presented in [14], makes it possible to construct a generalized parametric diagram of the grain dryer with a HP (Fig. 7).

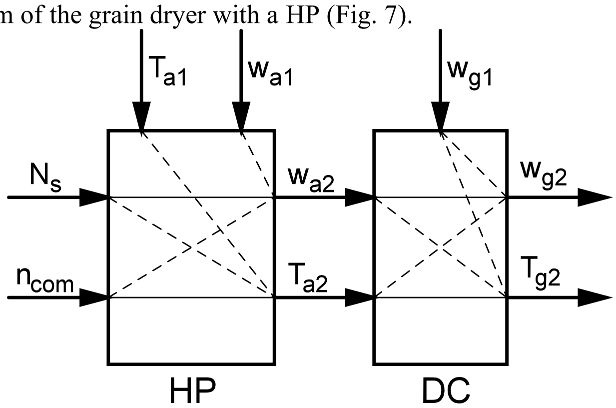


Fig. 7. Parametric diagram of the grain dryer with HP

In the diagram, the following designations are used: w_{g1} – initial rapeseed humidity, %; T_{g2} – rapeseed temperature, °C; w_{g2} – rapeseed humidity, %.

The static and dynamic characteristics show that, for all channels of coordinate transformation, the DC as a control object exhibits self-regulation properties and can be described by linear differential equations. There are many approaches to mathematical modeling of drying processes; however, in practice, models in the form of transfer functions are most commonly used. Considering that the grain dryer belongs to thermal systems, it is appropriate to represent the coordinate transformation channels (Fig. 7) using first- or second-order transfer functions. Using the methodology presented in [16], based on the available transient dynamic characteristics (Fig. 4 and Fig. 6), first- and second-order transfer functions were determined for all channels of the DC as a control object (Table 1).

Table 1

Mathematical models of the DC channels as a control object

Channel	First-order model	Second-order model
Control channels		
$w_{a2} - w_{g2}$	$\frac{0,37e^{-240s}}{540s+1}$	$\frac{0,37e^{-309s}}{(592s+1)(2000s+1)}$
$T_{a2} - T_{g2}$	$\frac{0,79e^{-391s}}{416s+1}$	$\frac{0,79e^{-382s}}{(483s+1)(1996s+1)}$
Cross-coupling links		
$w_{a2} - T_{g2}$	$\frac{-0.5e^{-119s}}{510s+1}$	$\frac{-0.5e^{-102.5s}}{(620s+1)(2101s+1)}$
$T_{a2} - w_{g2}$	$\frac{-0,81e^{-422s}}{390s+1}$	$\frac{-0,81e^{-370s}}{(652s+1)(2009s+1)}$
Controlled disturbance channels		
$w_{g1} - T_{g2}$	$\frac{0,71e^{-180s}}{526s+1}$	$\frac{0,71e^{-116s}}{(650s+1)(2048s+1)}$
$w_{g1} - w_{g2}$	$\frac{0,42e^{-191s}}{569s+1}$	$\frac{0,42e^{-121s}}{(574s+1)(1907s+1)}$

The transfer functions presented in Table 1 provide a sufficiently accurate description of the dynamic characteristics of the DC along the main channels of coordinate transformation. For the first-order models, the coefficient of determination is not less than 0.95, whereas for the second-order models it is not less than 0.98, which confirms their high adequacy.

Conclusions

Based on the research conducted, the following conclusions can be formulated.

As a result of the conducted studies, static and dynamic characteristics of the rapeseed drying process in a continuous-flow grain dryer equipped with a HP installation were obtained. Structural and parametric identification of the DC as a control object made it possible to distinguish two control channels of the thermal and moisture parameters of rapeseed, two cross-coupling links, and two controlled disturbance channels. The obtained transfer functions of these channels sufficiently accurately reproduce the dynamic properties of the grain dryer (coefficient of determination not less than 0.95) and can be used as a basis for the development of a simulation model and further analysis of HP grain drying operating modes.

The identified significant cross-effects of control actions and disturbances, which arise due to the mutual nonlinear dependence of the DA parameters and the seed material, indicate the necessity of developing effective control algorithms, which requires further research.

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