Optimization of energy costs for drying ferrocene-containing wastes of winemaking

J Gerber¹, A Zavaly¹, A Gavrilov², A Olshevskaya², N Kiyan¹

¹Academy of Bioresources and Environmental Management V.I. Vernadsky Crimean Federal University, Prospekt Vernadskogo 4, Simferopol, Republic of Crimea, 295007, Russia
²Don State Technical University, Ploshchad' Gagarina, 1, Rostov-on-Don, 344002, Russia

E-mail: gerber_1961@mail.ru

Abstract. The paper is devoted to the study of the processes of heat and mass exchange, when drying ferrocene containing wastes of winemaking (FWW), and to the preparation of those wastes to be fed to dairy cattle. The goals of the article are: to determine the amount of energy costs for drying FWW that are necessary for calculating the net cost of feed additives, and to estimate the economic efficiency of the suggested technological and technical solutions; and also to justify and develop the methods for estimating quantitative parameters when removing liquid from the wastes of wine production. Moisture and heat exchange are studied in the “heat agent - drying object” system for convective and infrared drying. A combined method is proposed for drying winemaking waste, to substantiate the sequence of stages and parameters of the process, a graph-analytic model, that is dwelled on the basic principles of convective and infrared drying, is designed. Numerical calculations helped to obtain graphical dependences of the energy costs of the drying process on the air velocity in the drying chamber at different temperatures of the air (for convective and infrared). The model of drying in the form of comparative graphical dependences of the reduced value of the drying speed to the heat flux on the moisture content of the mass subjected to drying is presented. Given the above data, it is recommended to use combined two-phase drying: in the first phase, use infrared radiation, when in the second phase - convective way, in order to reduce the humidity of ferrocene containing winemaking wastes from initial moisture content of 80% to the required value of 18-20% with the further use as neutralizing additives in the feed of dairy cattle. It is also suggested to use the renewable energy sources for heating in order to cut the expenses in the phase of convective drying.

1. Introduction

Vigorous human activity contributes to the creation of technogenic biogeochemical territories with an anomalous content of heavy metals. In particular, it is mercury, lead, cadmium, iron, zinc, copper, arsenic, fluorine. These substances enter the feed, and then livestock products. In addition, part of the area under forage crops, meadows and pastures contain radioactive elements which contents exceed standard values. This results in diseases of animals and people, a decrease in immunity, and a reduction in life expectancy.

There are many radioprotective techniques in animal husbandry that can reduce the level of radionuclides, including 137Cs in milk. These include such as organization of sown meadows and
pastures, due to their marginal and radical improvement, a change in the diets of animals, their feeding and management regimes. It is also worth to mention the approaches based on the addition of various elements to the diet, which block the absorption of radionuclides into the blood, when fodder enters the gastrointestinal tract, through competitive interaction with them, adsorption, and binding. It has been established that ferrocene possesses such properties [1]. Pure production of it is quite expensive.

It has been established that ferrocene contains pomace and sediment in the production of wines from grapes [2].

Previous studies on feeding dairy cows as an additive to ferrocene containing wastes of winemaking made it possible to conclude that their use to reduce 137Cs in livestock products is an effective way in the system of radioprotection measures in animal husbandry in areas contaminated with radionuclides and heavy metals [3, 4].

Heat and mass exchange processes play a significant part in the technological line of preparation for mixing feed additives with ferrocene containing wastes.

In connection with the foregoing, the goal of this work is to determine the conditions for the drying efficiency of winemaking waste for use as feed additives, justify the drying method that optimizes the energy costs of the process, and the economic efficiency of the proposed technological and technical solutions.

2. Materials and methods

Theoretical background of the drying process of FWW in preparation for feeding.

Since drying of winemaking waste to remove excess moisture is being discussed, the goal of this study is to substantiate and further develop methods for calculating quantitative parameters when liquid is evaporated from an open surface, to study heat and mass exchange under various conditions around the evaporation surface.

Moisture and heat exchange between the surface of the material and the ambience.

A large number of theoretical and experimental studies are devoted to the study of heat transfer under conditions of mass exchange process. The studied problems were considered in the works of A.V. Lykov, A.A. Gukhman, V.M. Smolsky, L.D. Berman, D. Dalton, G. Richmann, I. Newton, L. Prandtl, Y. Nakatani and others.

The results of studies carried out by various authors on the processes of heat and mass exchange during the evaporation of liquids are not sufficiently consistent, and sometimes they are contradictory: some studies note an increase in heat exchange in comparison with “pure” heat exchange, i.e. “heat exchange without mass exchange, in others - a decrease in the heat exchange coefficient.” In addition, there is no universal indicator that takes into account process parameters such as duration and total as well as specific energy costs.

The drying process consists of moving moisture inside the material, vaporization and removing moisture from the surface of the material. When wet material comes into contact with heated air, the liquid on the surface evaporates and leaves the surface of the material, passing into the ambient area. The evaporation of moisture from the surface creates a roll of moisture content between the subsequent layers and the surface layer, which causes the movement of moisture from the inner layers of the material to the surface. The presence of a temperature difference on the surface and in the central layers lingers the moisture transfer mechanism. Thermal diffusion of moisture occurs from warmer layers to layers with a lower temperature. Therefore, the characteristics of the drying process are determined by the mechanism of moisture exchange inside the material, the kinetics of evaporation and moisture transfer from the surface of the material into the ambience [5-15].

The total moisture flow of the material is:

\[ \nu \cdot p_o \cdot \nabla U - \alpha_m \cdot p_o \nabla T = -\alpha_m \cdot p_o (\nabla U + \delta \cdot \nabla T) \]  

where \( \alpha_m \) and \( \alpha_t^m \) - diffusion and thermal diffusion coefficients of moist bodies respectively;

\( p_o \) – density of the dry body;
\( \bar{V}U \) and \( \bar{V}T \) – difference in moisture content and temperature on the surface and inside of the material respectively;

\( \delta \) – relative coefficient of thermal diffusion (\( \delta = \frac{a_m}{a_n} \))

Since the method of combined drying is proposed, in order to justify the sequence of phases and process parameters, a grapho-analytical model for drying winemaking waste, based on the basic principles of convective and infrared drying, needs to be built.

Convective drying. Under isothermal conditions, as well as at small temperature differences in the boundary layer (during the phase of constant drying speed), the following formula can be used to determine the drying intensity:

\[
v_{c1} = a_{p} \cdot (p_n - p_c) = Nu_m \frac{D_p}{l} \cdot (p_n - p_c)
\]

where \( a_p \) - moisture exchange coefficient;

\( D_p \) – diffusion coefficient of vapor in air taken relative to the pressure difference;

\( p_n \) and \( p_c \) - partial vapor pressure values.

For the heat flow:

\[
q_{c1} = a_q \cdot (t_c - t_n) = Nu_p \frac{a_n}{l} \cdot (t_c - t_n)
\]

Index \( l \) means the surface of the material, when \( c \) - ambience;

\( a_q \) – heat exchange coefficient;

\( l \) – length of the body surface along gas flow;

\( \lambda_n \) – thermal conductivity of moist air.

Nusselt heat and mass transfer numbers (heat and mass transfer coefficients) are determined by the equations:

\[
Nu_p = a_q \cdot \frac{l}{\lambda_n} = K_1 + 0.59Re^{0.5}(1 + 1.55 \cdot 10^{-4}Re^{0.25})
\]

\[
Nu_m = a_p \cdot \frac{l}{p} = K_1 + 0.55Re^{0.5}(1 + 1.43 \cdot 10^{-4}Re^{0.25})
\]

where \( Re = \frac{V}{\nu} \) – Reynolds number,

\( V \) – velocity of heat transfer agent;

\( \nu \) – kinematic viscosity of the vapor-air mixture in the air boundary layer, \( m^2/s \);

\( K_1 \) – shape factor:

for thermal streamlined plates \( K_1=0 \);

for cylindrical surfaces \( K_1=0.3 \);

for spherical surfaces \( K_1=2 \).

Infrared drying.

The drying intensity when using infrared rays can be expressed by the formula:

\[
v_{c2} = r \cdot a_q (p_n - p_c) = \frac{r \cdot Nu_m}{l} \cdot (p_n - p_c)
\]

where \( r \) – specific heat of evaporation;

\( D \) – diffusion coefficient of vapor in the boundary layer.

The heat flow for the infrared drying is described by the following formula:

\[
q_{c2} = r \cdot (t_c - t_n) = (t_c - t_n)
\]

where \( I \) – radiant flux intensity:

\[
I = I_0 \exp (-K_\alpha \cdot b_m)
\]
I₀ – intensity of the radiant flux incident on the surface of the material;  
kₗ – infrared attenuation coefficient;  
bₘ – material layer thickness.

Since drying happens in two phases, first under the influence of infrared rays, then in a convective way, the total amount of heat for the drying period will be the sum of this indicator for the first and second phases (formulas 3 and 5):

\[ q_{ob} = N_u p \cdot \frac{\alpha_b}{l} \cdot (t_c - t_a) + \frac{r \cdot N_u p}{l} \cdot (t_c - t_a) = \frac{N_u p}{l} \cdot (t_c - t_a) \cdot (\alpha_b + r \cdot l) \]  

A universal indicator is needed to compare the effectiveness of the two types of drying described above. It should take into account process parameters such as the duration \( \tau_c \); total as well as specific energy costs \( Q_c, Q_{c,sp} \). Value \( K_v \) is recommended as a specified indicator, which is the ratio of the drying rate \( v_c \) to the heat flow \( q_c \). In order to determine the indicated value, the obtained earlier dependences are used. For convective drying, \( K_v \) is determined by dividing formula (2) by (3):

\[ K_{v1} = \frac{v_{c1}}{q_{c1}} = \frac{N_u m \cdot D_p \cdot (p_n - p_c)}{N_u p \cdot (t_c - t_a)} = \frac{N_u m \cdot D_p \cdot (p_n - p_c)}{N_u p \cdot (t_c - t_a)} \]  

In case of infrared drying, \( k_v \) is determined by dividing (4) by (5):

\[ K_{v2} = \frac{v_{c2}}{q_{c2}} = \frac{r \cdot N_u m \cdot (p_n - p_c)}{r \cdot N_u p \cdot (t_c - t_a)} = \frac{N_u m \cdot D \cdot (p_n - p_c)}{N_u p \cdot (t_c - t_a)} \]  

3. Study results

The calculations performed by the numerical method made it possible to obtain graphical dependencies, which are given below. The graphs (Figure 1, 2) show the dependence of the energy costs of the process on the air velocity in the drying chamber at various temperatures of the air in contact with the drying object.

![Figure 1](image-url)

**Figure 1.** Dependence of energy costs for drying \( Q_c \) on the air velocity \( \nu_{air} \) in the drying chamber (convective drying).
Figure 2. Dependence of energy costs for drying $Q_c$ on the air velocity $\upsilon_{\text{air}}$ in the drying chamber (infrared drying).

The graph (Figure 3) shows the drying model in the form of comparative graphical dependences of the reduced value of $k_\nu$ on the moisture content of the mass subjected to drying.

4. Discussion
The obtained model allows to draw the following conclusions.
In the initial period of drying, the process speed is higher with IR drying (this reflects a larger value of $k_\nu$ on the graph); this is explained by the fact that infrared rays penetrate deep into the material and heat it up, a temperature gradient is formed between the drying material and the surrounding air, which
creates good conditions for the movement of moisture to the surface layer; when the moisture content of the material decreases, the speed also decreases.

Further, the speed of the process in the two described methods is equalized, and then the drying speed with the convective method exceeds this value for infrared drying; This is explained by the fact that the moisture that has moved to the surface layer evaporates faster, in the case of more intensive removal of moisture by a thermal agent (its higher moisture absorption capacity), which occurs with the convective method.

The energy balance of drying. For each drying unit, the first law of thermodynamics on the constancy of the sum of energy flows in a closed system is valid [2]. Therefore, for a continuous drying plant in a steady state process, the energy balance equation is the following:

\[ m_{dr,ent} \cdot h_{m,ent} + \sum m_{b,ent} \cdot h_{b,ent} + Q_{fc} \cdot R + P_a = \sum m_{dr,ex} \cdot h_{m,ex} + \sum m_s \cdot h_{b,ex} + \sum Q \]  \hspace{1cm} (10)

where \( h_{m,ent} \) – specific enthalpy of source material supplied to the drying plant, kcal/kg;
\( h_{b,ent} \) – specific enthalpy of air supplied to the drying plant, kcal/kg;
\( Q_{fc} \) – fuel consumption per hour, kg/h;
\( R \) – fuel energy value, kcal/kg;
\( P_a \) – active power of electric consumers, kcal/kg;
\( h_{m,ex} \) – specific enthalpy of material at the outlet of the drying plant, kcal/kg;
\( h_{b,ex} \) – specific enthalpy of air at the outlet of the drying plant, kcal/kg;
\( \sum Q \) – total energy losses, kcal/h.

In most cases, it is possible to determine the values necessary for meeting the energy balance, with the exception of heat loss. The value \( \sum Q \) includes the loss of thermal energy. This includes losses due to incomplete combustion of the fuel, entrainment of heat with ash, exhaust gases, losses due to radiation and convection.

In order to create an ideal balance of energy and mass flows in a drying unit, the following parameters must be determined: ambient air - temperature, moisture content, losses at the dryer inlet; discharged air - temperature, moisture content, losses at the dryer outlet; source material - humidity, temperature, product flow; dried material - humidity, temperature, product flow; fuel: consumption, energy value, chemical composition; heat agent - flow, enthalpy difference at the inlet and outlet of the dryer; electric power - active power; energy losses - convection and radiation, losses during the combustion of a heat transfer agent; air to control the temperature of the drying agent - enthalpy.

The total heat loss is difficult to measure directly, therefore, in order to determine it, it is recommended to use well-known equations and find these losses by calculation.

Heat consumption for the drying process. According to the law of conservation of energy, all the heat supplied to the material subjected to drying is equal to the heat spent on the evaporation of moisture and on its heating. Let the total surface of the material be \( S \), it contains some moisture mass \( m_v \) and dry matter mass \( m_c \). Denote the specific heat capacity of air and absolute dry matter respectively \( c_v \) and \( c_c \). Then the amount of the heat required to heat up the body per time unit will be equal to:

\[ (C_c \cdot m_c + C_v \cdot m_v) \cdot \frac{dt}{d_t} \]  \hspace{1cm} (11)

where \( t \) – average material temperature.

The heat spent on evaporating moisture is:

\[ r \cdot \frac{dm_v}{d_t} = r \cdot m_o \cdot \frac{dU}{d_t} \]  \hspace{1cm} (12)

where \( U = \frac{m_o}{m_v} \)
\( r \) – specific heat of evaporation.
Total heat, that is used to heat up the material and evaporate the moisture, is equal to the amount of heat supplied per time unit to the entire surface. Summing formulas (11) and (12), and then dividing both components by $V$, we obtain:

$$q_n = (C_c + C_v)\rho_0 \cdot R_v \cdot r \frac{du}{dt}$$

(13)

where $R_v$ – ratio of the volume of dry matter $V_c$ to the surface area $S$ of the moist body, ($R_v = \frac{V_c}{S}$).

Denote the heat capacity of a moist body by $C = C_c + C_v$, then:

$$q_n = \rho_0 \cdot R_v \cdot r \frac{du}{dt} \cdot \left(1 + \frac{c}{r} \frac{dt}{du}\right)$$

(14)

The ratio $\frac{dt}{du}$ characterizes the increase in the average temperature of the material with a change in moisture content per unit during the drying process.

The value $\frac{c}{r} \frac{dt}{du}$ is dimensionless; it shows the ratio of the amount of the heat supplied to the material to heat up to the amount of the heat used to evaporate moisture over an infinitesimal period of time.

Thus, the value $\frac{c}{r} \frac{dt}{du}$ - the Rebinder criterion, which is the main criterion for the kinetics of drying. It determines the degree of energy efficiency of the process and equals to:

$$q_n = \rho_0 \cdot R_v \cdot r \frac{du}{dt} \cdot (1 + R_u)$$

(15)

When the velocity is constant, the Rebinder criterion is zero, then:

$$q_n(0) = q_o \cdot R_v \cdot r \cdot \frac{N}{100} = \text{const}$$

(16)

5. Conclusion

- Considering the above, the energy efficiency of the drying process is the higher the closer the amount of heat supplied to heat up the material to be dried (FWW) is closer to the amount of heat used to evaporate moisture per time unit, i.e. drying kinetics criterion index (Rebinder criterion).
- For a comparative assessment of drying methods in a particular case, a universal indicator $k_v$ is proposed, where it is the ratio of the drying velocity $u_c$ to the heat flow $q_c$.
- Considering the above data, it is recommended to use combined two-phase drying: by infrared radiation in the first phase and convective in the second one, in order to reduce the humidity of ferrocene containing wastes of winemaking from an initial humidity of 80% to the required value of 18-20% [4] with the aim of using them as neutralizing additives in the feed of dairy animals.
- It is recommended to use renewable energy sources for heating up the agent in order to reduce energy costs in the phase of convective drying.

References

[1] Gudkov I, Lazarev M 2003 Nauchnoye obespecheniye ustoychivogo razvitiya sel's'kogo yekhnologii v Lesostepi Ukrainy (K.: Izdatel'stvo «Alefa») volume 1 pp 747–775
[2] Gerber Y 2013 Nauchnyye trudy Yuzhnogo filiala Natsional'nogo universiteta bioresursov i prirodopol'zovaniya Ukrainy «Krymskiy agroteknologicheskiy universitet» Seriya Tekhnicheskiye nauki pp 6-13
[3] Kiptelaya L, Zagorul'ko A 2014 Nauchnyy zhurnal NIU ITMO Seriya «Protsessy i apparaty pishchevykh proizvodstv»3 pp 80-86
[4] Vechtomova Y, Lazarev M, Gudkov I, Gurenko A, Frunze V 2006 Doklady uchastnikov 5-y
Mezhdunarodny nauchno-prakticheskiy konferentsii (Zhitomir: Izdatel'stvo DAU) pp 173–178

[5] Afon'kina V, Zakhakhatnov V, Mayorov V, Popov V 2016Vestnik Mordovskogo universiteta DOI: 10.15507/0236-2910.026.201601.032-039

[6] Gerber Y, Gavrilov A, Verbitskiy A, Sirotkina E2016Izvestiya sel'skokhozyaystvennoy nauki Tavridy Simferopol/7 170pp 52-59

[7] Gayfullina R, Kurbangaleyev M, Zaripov Z, Willson B 2011Vestnik kazanskogo tekhnologicheskogo universiteta7 pp 42-45

[8] Kas'yanov G, Myakinnikova Y, Syazin I, Karikurubu Z2014Tekhnika i tekhnologiya pishchevykh proizvodstv2

[9] Korotkiy A, Rasshchepkin D, Fedorov O2014Tekhnika i tekhnologiya pishchevykh proizvodstv4

[10] Tepe K, Agbenotowossi K, Djeteli G, Ouro-Djobo S, Napo K, Pichon L 2010 Al'ternativnaya energetika i ekologiya2 82 pp22-27

[11] Kas'yanov G, Syazin I, Myakinnikova Y, Karikurubu Z2014Zhurnal yekhnologi pishchevoy i pererabatyvayushchey promyshlennosti APK – produkty zdorovogo pitaniya2 pp 10-14

[12] EngovatovaV, Demin V, OvchinnikovaYEngovatovA 2015Nauchnye trudy Kubanskogo gosudarstvennogo tehnologicheskogo universiteta4pp301-312

[13] Milovanov I 2013Trudy Kubanskogo gosudarstvennogo agrarnogo universiteta44 pp278-281

[14] http://e-koncept.ru/2015/65324.htm.

[15] http://www.avante.com.ua/rus/library/lib perspektiv soln energetiki.htm.