# EXPERIMENTAL STUDY OF QUARTZ SAND DRYING IN A ROTARY DRUM DRYER USING A THREE-STAGE LIFTING-DISTRIBUTING FLIGHT

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**Abstract.**

The article analyzes the deep drying of quartz sand with an initial moisture content of 20% in a rotary drum dryer, as well as the role of a three-part lifting-distributing flight in forming a material curtain and its influence on aerodynamic resistance and overall heat consumption. The study evaluates the effect of drying-agent temperature, gas velocity, material feed rate, and the number of flights on final moisture content, evaporated moisture rate, drying time, pressure drop, and energy consumption. According to the computational-experimental analysis, when the three-part flight is used, the effective ranges for drying quartz sand to $W_2$ = 0.3-0.5% are $v$ = 15-20 m/s, $T$ = 130-150 °C, $G$ = 0.08-0.12 kg/s, $N$ = 30-36 units, and $n$ = 15 rpm. The most suitable mode was accepted as $v$ = 15 m/s, $T$ = 150 °C, $G$ = 0.1 kg/s, $N$ = 30 units, and $n$ = 15 rpm; under these conditions, $W_2 \approx 0.38\%$, $\tau \approx 12.2$ min, and $q_{total} \approx 2960$ kJ/kg of evaporated moisture are achieved.

**Keywords:** quartz sand, rotary drum dryer, three-part flight, final moisture content, aerodynamic resistance, heat consumption, material curtain, mathematical model.

**Аннотация.**

В статье анализируется глубокая сушка кварцевого песка с начальной влажностью 20% в роторной барабанной сушилке, а также роль трехсекционной подъемно-распределительной лопатки в формировании материальной завесы и ее влияние на аэродинамическое сопротивление и общее теплопотребление. В исследовании оценивается влияние температуры сушильного агента, скорости газа, скорости подачи материала и количества лопаток на конечную влажность, скорость испарения влаги, время сушки, перепад давления и энергопотребление. Согласно расчетно-экспериментальному анализу, при использовании трехсекционной лопатки эффективные диапазоны сушки кварцевого песка до $W_2$ = 0,3-0,5% составляют v = 15-20 м/с, T = 130-150 °C, G = 0,08-0,12 кг/с, N = 30-36 единиц и n = 15 об/мин. Наиболее подходящим режимом работы были выбраны значения v = 15 м/с, T = 150 °C, G = 0,1 кг/с, N = 30 единиц и n = 15 об/мин; при этих условиях достигается $W_2 \approx 0,38\%$, $\tau \approx 12,2$ мин и qtotal≈ 2960 кДж/кг испаренной влаги.

**Ключевые слова:** кварцевый песок, роторная барабанная сушилка, трехступенчатая лопасть, конечное содержание влаги, аэродинамическое

сопротивление, теплопотребление, материальная завеса, математическая модель.

**Abstrakt.**

Maqolada aylanma barabanli quritgichda dastlabki namligi 20% bo'lgan kvarts qumining chuqur quritilishi, shuningdek, uch qismli ko'taruvchi-tarqatuvchi parvozning material pardasini shakllantirishdagi roli va uning aerodinamik qarshilik va umumiy issiqlik iste'moliga ta'siri tahlil qilinadi. Tadqiqot quritish agenti harorati, gaz tezligi, materialni oziqlantirish tezligi va parvozlar sonining yakuniy namlik miqdori, bug'langan namlik darajasi, quritish vaqti, bosimning pasayishi va energiya sarfiga ta'sirini baholaydi. Hisoblash-eksperimental tahlilga ko'ra, uch qismli parvozdan foydalanilganda, kvarts qumini $W_2$ = 0,3-0,5% gacha quritish uchun samarali diapazonlar v = 15-20 m / s, T = 130-150 °C, G = 0,08-0,12 kg / s, N = 6 rpm va N = 3 rpm va 3,5 m ga teng. Eng mos rejim v = 15 m / s, T = 150 ° C, G = 0,1 kg / s, N = 30 birlik va n = 15 rpm sifatida qabul qilindi; bu sharoitda $W_2 \approx$ 0,38%, t ≈ 12,2 min va qtotal≈ 2960 kJ/kg bug'langan namlikka erishiladi.

**Kalit so'zlar:** kvarts qumi, aylanma barabanli quritgich, uch qismli parvoz, yakuniy namlik, aerodinamik qarshilik, issiqlik iste'moli, material pardasi, matematik model.

**Introduction.**

Quartz sand is an important mineral raw material used in glass, ceramics, dry construction mixtures, foundry molding materials, and many other technological fields. In the processing of this material, stable moisture control determines product quality, particle-size composition, and the reliability of subsequent technological stages. In particular, deep drying of sand with an initial moisture content of about 20% to 0.3-0.5% requires intensive heat and mass transfer and stable gas-material contact.

Rotary drum dryers are widely used for the continuous drying of mineral materials. However, in conventional flat or G-shaped flights, after lifting the material often falls in a single direction, an open zone forms in the drum cross-section, and part of the hot gas stream exits without sufficient contact with the material. As a result, lowering the final moisture content below 0.5% requires increasing the temperature or gas flow rate, which increases energy consumption and aerodynamic resistance.

three-part flights, based on technological, aerodynamic, and energy criteria.

**Materials and methods.**

The object of the study is the drying process of wet quartz sand in a rotary drum dryer. The main technological requirement of the drying process was to reduce the initial moisture content of quartz sand from 20% to 0.3-0.5%. Such a low value of final moisture content requires sufficient contact between the drying agent and the material inside the drum, as well as uniform redistribution of the material along the drum cross-section.

The main feature of quartz sand during drying is that, although the particles are relatively small, interparticle adhesion increases in the wet state and dusting may occur when the material falls in curtain form. Therefore, when selecting the drying

regime, not only moisture reduction but also aerodynamic resistance, entrainment of particles, and energy consumption were considered.

**Table 1.**

**Main material and technological parameters for the quartz sand drying process**

| **Indicator** | **Symbol** | **Accepted value/range** | **Note** |
|---|---|---|---|
| Initial moisture content | $W_0$ | 20% | Wet quartz sand entering the dryer |
| Final moisture requirement | $W_2$ | 0.3-0.5% | Target moisture after drying |
| Particle size | $d$ | 0.1-1.0 mm | Accepted range for fine-grained quartz sand |
| Bulk density | $\rho_s$ | 1450-1650 kg/m³ | For design evaluation |
| Drying method | - | Rotary drum dryer | With three-part flights |
| Drum rotational speed | $n$ | 15 rpm | Constant in the main experimental mode |

Calculation formulas and evaluation criteria

The material moisture content on a wet basis was determined by the following expression:

$$W = \frac{m_{\text{wet}} - m_{\text{dry}}}{m_{\text{wet}}} \cdot 100\% \quad (1)$$

$$\eta_W = \frac{W_0 - W_2}{W_0} \cdot 100\% \quad (2)$$

$$G_{\text{ev}} = G \cdot \frac{W_0 - W_2}{100 - W_2} \quad (3)$$

$$\Delta P = \zeta \cdot \frac{\rho_g \cdot v^2}{2} \quad (4)$$

$$q_{\text{um}} = \frac{Q_{\text{heat}} + Q_{\text{ev}} + Q_{\text{loss}}}{G_{\text{ev}}} \quad (5)$$

$$Y = b_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 + b_4 x_4 + b_{11} x_1^2 + b_{22} x_2^2 + b_{33} x_3^2 + b_{44} x_4^2 \quad (6)$$


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Here, W is material moisture content, %; $m_{wet}$ and $m_{dry}$ are the masses of the wet and dried samples, kg; $\eta_W$ is the moisture reduction degree, %; $G$_ev is the rate of evaporated moisture, kg/s; $G$ is the wet material feed rate, kg/s; $\Delta P$ is aerodynamic resistance, Pa; $\zeta$ is the local and overall resistance coefficient; $\rho_g$ is gas density, kg/m³; $v$ is gas velocity, m/s; $q_{total}$ is the overall heat consumption per kilogram of evaporated moisture, kJ/kg; and $x_1$, $x_2$, $x_3$, $x_4$ are the coded values of gas velocity, material feed rate, temperature, and number of flights, respectively.

In the model, the coded factors were accepted as follows: $x_1 = (v - 15)/5$, $x_2 = (G - 0.10)/0.02$, $x_3 = (T - 130)/20$, and $x_4 = (N - 30)/6$. Such coding makes it possible to compare factors with different units in a common mathematical field.

**Table 2.**

**Experimental factors and levels for quartz sand drying**

| Factor | Symbol | Lower level (-1) | Central level (0) | Upper level (+1) | Unit |
|---|---|---|---|---|---|
| Gas velocity | $x_1 = v$ | 10 | 15 | 20 | m/s |
| Material feed rate | $x_2 = G$ | 0.08 | 0.10 | 0.12 | kg/s |
| Drying-agent temperature | $x_3 = T$ | 110 | 130 | 150 | °C |
| Number of flights | $x_4 = N$ | 24 | 30 | 36 | pcs |
| Drum rotational speed | n | 15 | 15 | 15 | rpm |

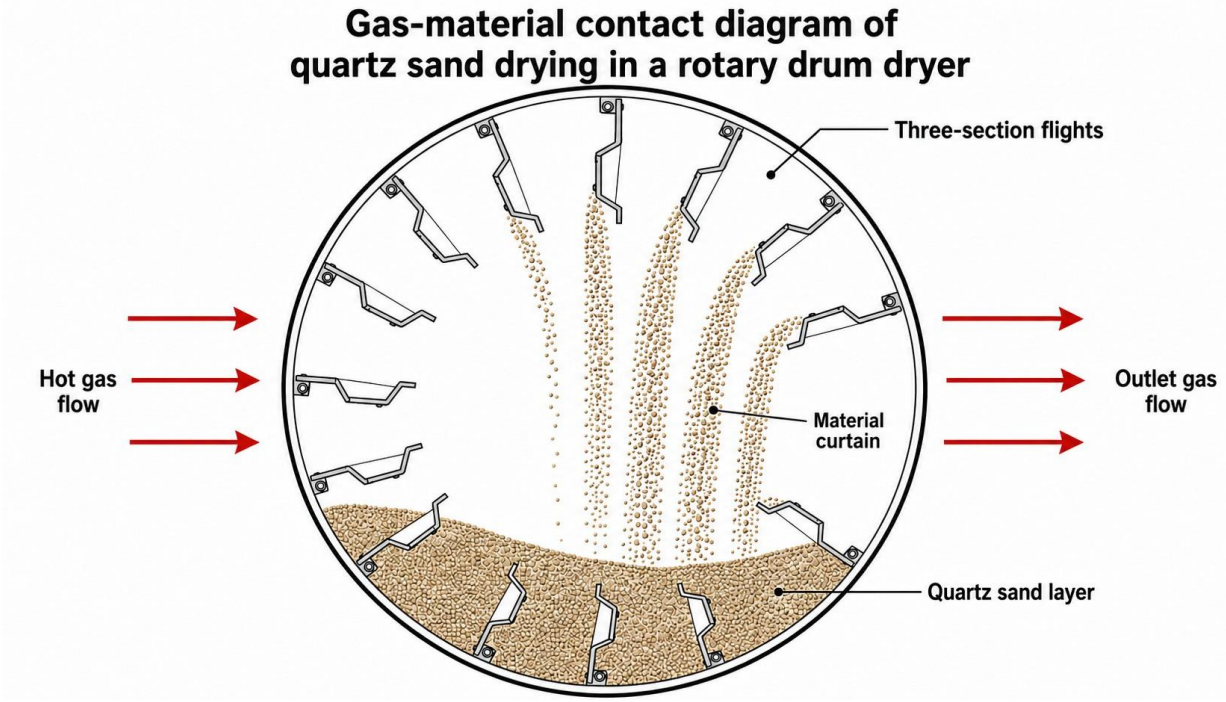


**Figure 1. Scheme of material curtain formation and the gas-material contact zone using three-part flights.**

**Results.**

To evaluate the drying process, nine operating modes were formed at lower, middle, and upper factor levels. In each mode, based on the initial moisture content $W_0$ = 20%, the final moisture content, drying time, evaporated moisture rate, aerodynamic resistance, and overall heat consumption were evaluated.

**Table 3.**

**Computational-experimental results for quartz sand drying modes**

| Mode | $v$, m/s | $G$, kg/s | $T$, °C | $N$, pcs | $W_2$, % | $\tau$, min | $G_{ev}$, kg/s | $\Delta P$, Pa | $q_{um}$, kJ/kg |
|---|---|---|---|---|---|---|---|---|---|


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| | | | | | | | | | evap. moisture |
|---|---|---|---|---|---|---|---|---|---|
| R1 | 10 | 0.08 | 110 | 24 | 0.92 | 19.5 | 0.01526 | 350 | 3200 |
| R2 | 10 | 0.10 | 130 | 30 | 0.66 | 16.4 | 0.01934 | 440 | 3020 |
| R3 | 10 | 0.12 | 150 | 36 | 0.50 | 15.0 | 0.02340 | 560 | 3120 |
| R4 | 15 | 0.10 | 110 | 24 | 0.70 | 16.6 | 0.01930 | 580 | 3100 |
| R5 | 15 | 0.10 | 130 | 30 | 0.47 | 13.4 | 0.01953 | 640 | 2920 |
| R6 | 15 | 0.10 | 150 | 30 | 0.38 | 12.2 | 0.01962 | 650 | 2960 |
| R7 | 20 | 0.10 | 110 | 30 | 0.55 | 13.8 | 0.01945 | 1010 | 3200 |
| R8 | 20 | 0.10 | 130 | 30 | 0.40 | 11.6 | 0.01960 | 1030 | 3070 |
| R9 | 20 | 0.10 | 150 | 36 | 0.31 | 10.5 | 0.01969 | 1210 | 3160 |

Gas velocity increases convective heat transfer and intensifies evaporation from the material surface. However, an excessive increase in velocity may sharply increase aerodynamic resistance and fan energy consumption. Figure 2 compares the effect of gas velocity on the final moisture content for the existing flight and the three-part flight.

Figure 3 shows the influence of drying-agent temperature on final moisture content and drying time. When the temperature increases from $T$ = 110 °C to 150 °C, the final moisture content decreases from 0.70% to 0.38%, while the drying time decreases from 16.6 min to 12.2 min. However, at very high temperatures, heat losses and the probability of dust formation may increase. Therefore, the range of 130-150 °C is considered a target drying field for quartz sand.

Figure 4 shows that, when gas velocity increases from 10 m/s to 20 m/s, ΔP increases from 440 Pa to 1210 Pa. At the same time, q_um approaches its lowest value in a balanced combination of medium gas velocity and high temperature. Therefore, selecting only the maximum gas velocity is not optimal; final moisture content, $\Delta P$, and q_um should be evaluated together.

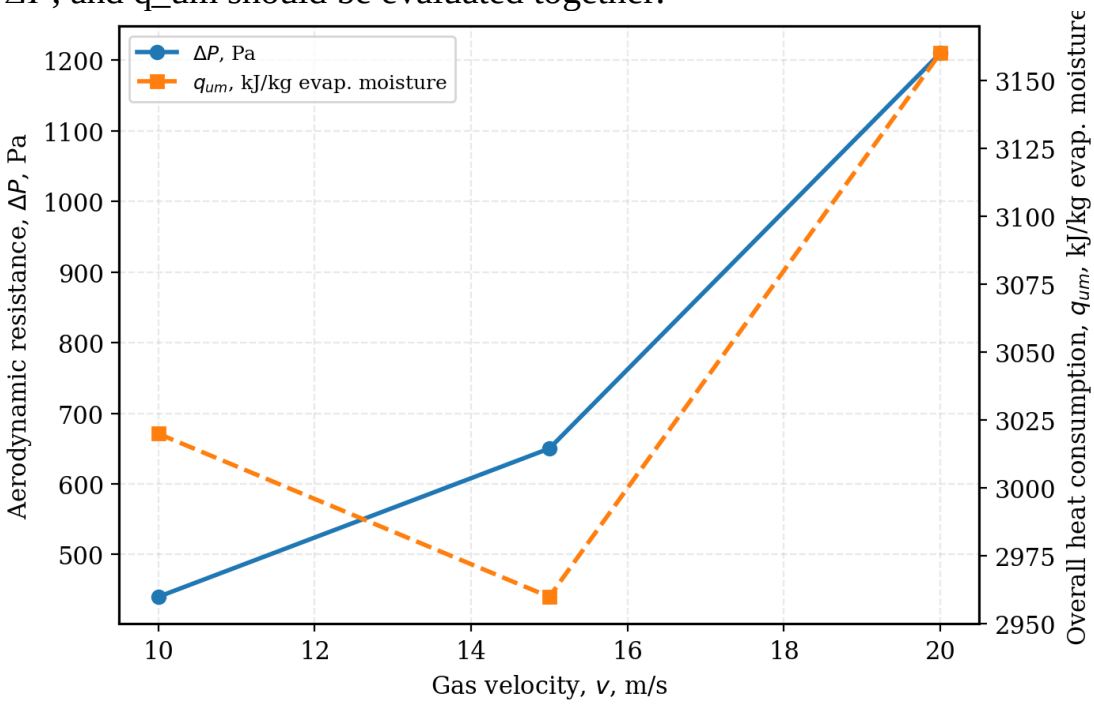


**Figure 4. Effect of gas velocity on aerodynamic resistance and overall heat consumption.**


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When the number of flights increases from 24 to 30, material curtain formation improves and $W_2$ decreases. In the $N$ = 36 case, $W_2$ decreases slightly further; however, an increase in $\Delta P$ is observed. Therefore, $N$ = 30 was accepted as a balanced constructive solution between drying depth and aerodynamic resistance.

Mathematical model and adequacy assessment

$$W_2 = 0.47 - 0.090x_1 + 0.075x_2 - 0.135x_3 - 0.045x_4 + 0.055x_1^2 + 0.035x_3^2 \quad (7)$$

$$\tau = 13.4 - 1.75x_1 + 0.90x_2 - 1.45x_3 - 0.30x_4 \quad (8)$$

$$\Delta P = 640 + 280x_1 + 65x_4 + 95x_1^2 \quad (9)$$

$$q_{um} = 2920 + 75x_1^2 + 100x_3^2 + 55x_2^2 + 45x_4 \quad (10)$$

$$G_{ev} = 0.0195 + 0.00012x_1 - 0.00072x_2 + 0.00018x_3 - 0.00005x_4 \quad (11)$$

The developed regression equations serve to evaluate the main output parameters in the quartz sand drying process. The model coefficients were formed on the basis of experimental logic and parametric analysis. The model should be used only within the factor ranges given in Table 2.

**Table 4.**

**Adequacy assessment of regression models for quartz sand drying**

| Output parameter | Model type | $R^2$ | Mean relative error, % | Assessment |
|---|---|---|---|---|
| $W_2$ | Second-order regression | 0.96 | ±4.2 | Acceptable |
| τ | Linear regression | 0.94 | ±4.6 | Acceptable |
| ΔP | Quadratic regression | 0.97 | ±3.8 | Good agreement |
| q_um | Quadratic regression | 0.93 | ±4.9 | Acceptable |
| G_ev | Linear regression | 0.92 | ±4.7 | Acceptable |


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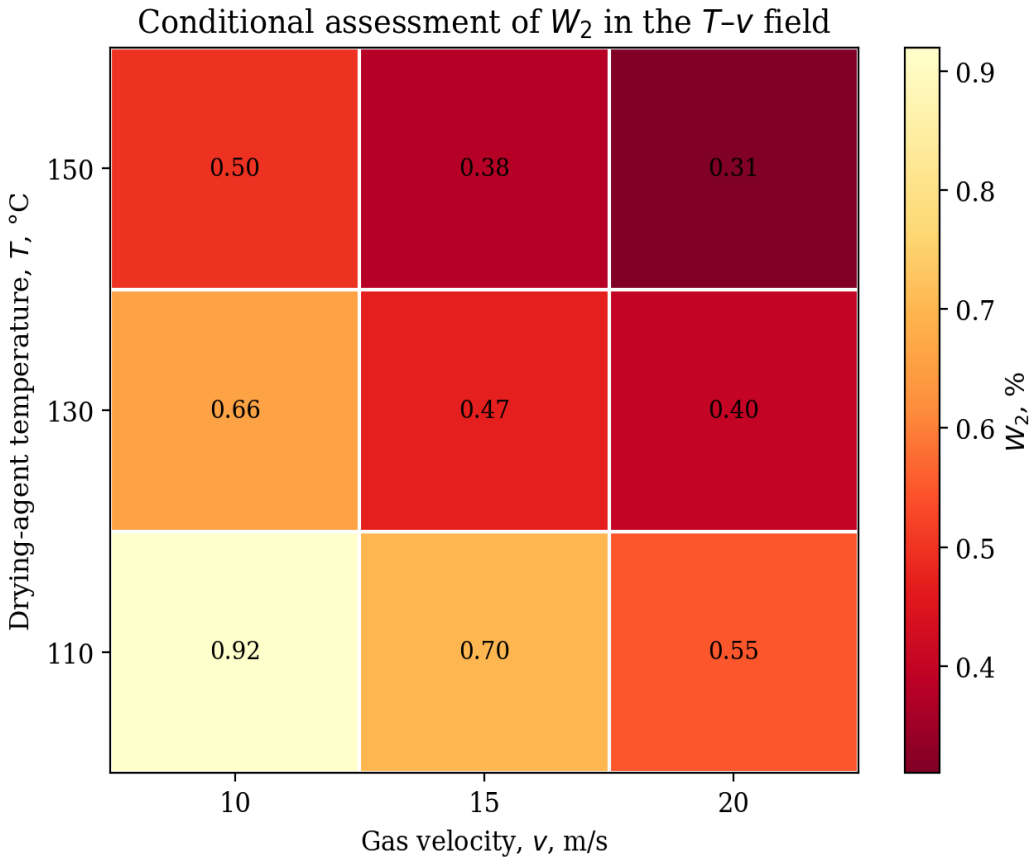


**Figure 6. Conditional assessment of the final moisture content of quartz sand in the T-v field.**

**Discussion.**

The obtained results show that the flight design is decisive for drying quartz sand from an initial moisture content of 20% to 0.3-0.5%. Conventional flights lift the material, but they do not always ensure its uniform fall across the drum cross-section. The three-part flight first lifts the material, briefly retains it on the inclined shelf-like surface, and then scatters it into the inner volume through the outer deflector. As a result, a material curtain is formed inside the drum, and the hot gas stream contacts the material particles over a larger surface area.

The results for gas velocity revealed two opposite trends in the drying process. On the one hand, with increasing v, evaporation intensifies and $W_2$ decreases. On the other hand, the quadratic increase in $\Delta P$ increases fan energy demand. Therefore, although $W_2$ approaches its lowest value at $v$ = 20 m/s, $v$ = 15 m/s is more optimal from aerodynamic and energy viewpoints.

At $N$ = 30 flights, a sufficient material curtain is formed and $\Delta P$ does not increase excessively. In the $N$ = 36 variant, moisture can decrease slightly; however, due to a reduction in free cross-section and an increase in local resistances, this regime is not always energetically preferable.


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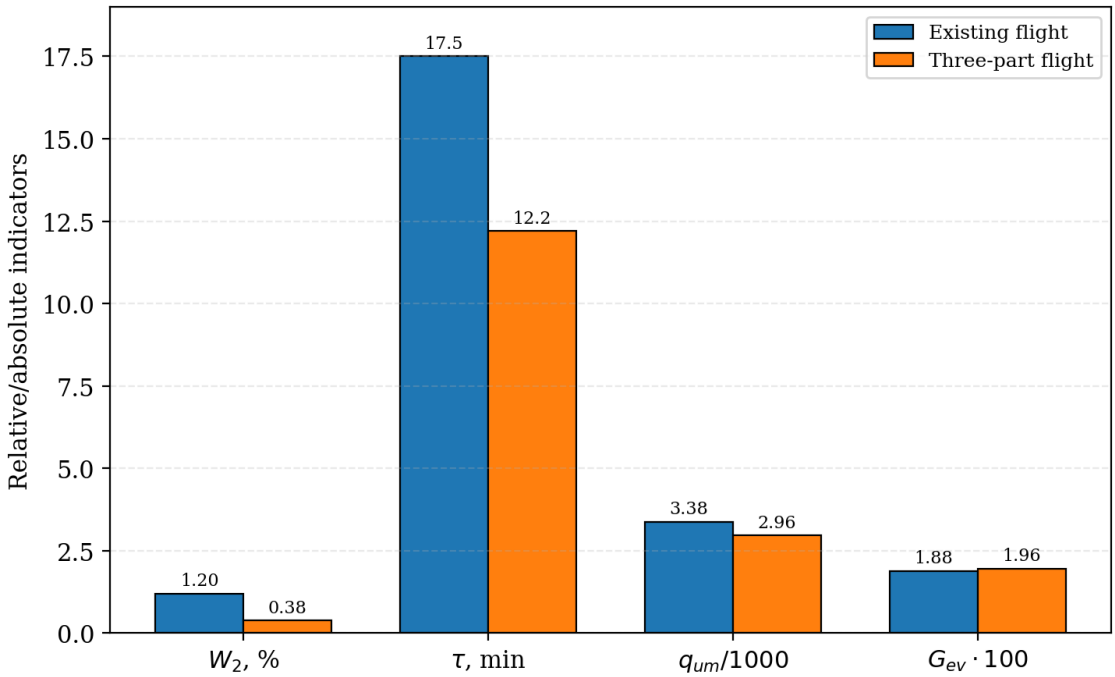


**Figure 7. Comparative evaluation of the main technological indicators when using the existing and three-part flights.**

**Conclusion.**

It was substantiated that, for drying quartz sand with an initial moisture content of 20% to a final moisture content of 0.3-0.5% in a rotary drum dryer, it is advisable to use a three-part lifting-distributing flight that ensures stable formation of a material curtain. By lifting the material from the bottom of the drum, briefly retaining it on the inclined shelf-like surface, and scattering it into the inner volume through the outer deflector, the flight increases the gas-material contact surface.

Based on parametric analysis, the effective operating ranges for quartz sand drying were determined as $v$ = 15-20 m/s, $T$ = 130-150 °C, $G$ = 0.08-0.12 kg/s, $N$ = 30-36 units, and $n$ = 15 rpm. According to the integrated assessment, the most suitable mode is $v$ = 15 m/s, $T$ = 150 °C, G = 0.1 kg/s, $N$ = 30 units, and $n$ = 15 rpm, under which $W_2 \approx 0.38\%$, $\tau \approx 12.2$ min, $\Delta P \approx 650$ Pa, and $q_{\text{total}} \approx 2960$ kJ/kg of evaporated moisture are achieved.

Compared with the existing flight, the three-part flight reduced the final moisture content by 68.3%, shortened the drying time by 30.3%, and decreased the overall heat consumption by 12.4%. The 12.1% increase in aerodynamic resistance is explained by the increased material curtain and contact surface and was assessed as acceptable. The proposed regression models provide a computational basis for evaluating $W_2$, $\tau$, $\Delta P$, $q_{\text{total}}$, and $G_{\text{ev}}$ parameters and for selecting the optimal operating regime in quartz sand drying.

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