ASSESSMENT OF THE IMPACT OF SOME METEOROLOGICAL FACTORS ON THE ENERGY AND ENVIRONMENTAL EFFICIENCY OF TUBE ROTARY KILNS

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ABSTRACT

It is emphasized that rotary kilns are units for high-temperature heat treatment of a wide range of materials in a continuous technological process. This type of equipment is used intensively in many industrial branches such as chemical, metallurgical, silicate, pharmaceutical and others. In metallurgy, these installations find application at heat treatment of bulk materials, for example at reduction of oxide ores, at calcination of limestone, drying of copper sulfide charge, cleaning of metal shavings from machine oil and others.

An overview of the ways of heat transfer to the material processed in a given rotary kiln, as well as of the basic mathematical models for describing the complex transport phenomena in the considered units is made.

An accent is put on the fact that due to their large size, rotary kilns are often installed on open areas within the industrial sites to whose equipment they are included. The variable weather conditions can have a significant impact on the energy flow that leaves the cage of such a unit. It dissipates uselessly in the environment, which is accepted as a reason to be widely characterized as "heat loss". This concept contains some conditionality, because according to the law of conservation of energy, it can not be created and disappear, but is transformed from one species to another. Nevertheless, the convenience of expression it offers has led to its use in the present statement.

The proposed work is focused on the analysis of results obtained from calculating the heat loss from a rotary kiln to the surrounding outside air at typical for the latitude and climatic features of Bulgaria average annual temperature and a presence of relatively weak constant wind.

As a result of the performed calculations, conclusions have been made about the ratios between the individual heat fluxes from the outer surface of the unit to the environment, as well as practically oriented recommendations for improving the energy and environmental efficiency of the discussed equipment

Keywords: *rotary kilns, heat loss, meteorological factors, wind, energy and environmental efficiency.*

INTRODUCTION

Rotary kilns are units for high-temperature heat treatment of various materials in a continuous technological process. In the past, they were associated only with the production of cement [1], but their field of application is gradually expanding and developing [1 - 5]. At present, these units are used in many industrial branches such as chemical, metallurgical, silicate, pharmaceutical and others, as well as in the utilities for combustion of residual materials from various production installations or household waste [6]. They can carry out processes of drying, incineration, mixing, heating, frying, cooling, humidification, calcination, reduction, sintering, melting, gasification, dehydration and reactions between gas and solid phase [7].

In metallurgy, the discussed facilities find application for heat treatment of bulk materials [8 - 10], for example at reduction of oxide ores, at calcination of limestone, drying of copper sulfide charge, cleaning of metal shavings from machine oil and others [11 - 13].

Various and complex processes of pulse, heat and mass transfer take place in each rotary kiln. Every one of them is influenced both by the main factor for itself, representing the characteristic driving force for the relevant phenomenon, and by such input parameters that are not decisive for the observed process, but also affect it [14, 15].

In directly heated rotary kilns, the material to be processed is poured into the upper end of the tube cage and transported continuously to the lower end of the inclined drum by rotating it around its own longitudinal axis. The depth of the particle layer in the cylinder decreases along its length. To reach the required temperature in the working space of the furnace, primary energy carriers such as natural gas, fuel oil or pulverized coal are used. The burner can be installed against or coinciding with the direction of movement of the material in the unit. The first orientation is preferable due to the significant advantages of the countercurrent flow scheme of movement of both media through each heat and mass exchanging apparatus [14].

The indirectly heated rotary kilns are a separate category of equipment that is externally warmed. They are designed especially for situations where direct contact between the material and the gas formed during combustion of the energy carrier must not be allowed. In this case, the heat is supplied from the side of the rotary kiln [1]. The gases moving above the surface of the treated substance contain volatile stuffs and components from the physical-chemical reactions taking place in the solid phase, which requires their subsequent purification. Due to the lower thermal efficiency of external heating, furnaces of this type are characterized by quite modest performances and small sizes.

Based on the above, it can be summarized that there are three ways for heat transfer to the material treated in a rotary kiln [14]:

- By means of the hot gases in the working space of the unit, which are usually generated by a combustion process in it. This is the most common case, typical for furnaces with internal heating.
- Through external warming of the wall, as is the principle of operation of the units with indirect supply of the required amount of heat for the process.
- From the hot gases to the unheated wall from the outside and then, due to its rotation - to the material.

The mechanisms for heat transfer to the individual zones of the working space of the discussed units depending on the presence or absence of a layer of particles on them are presented in [16]. One of the best models with rendering an account of the emitting in tube rotary kilns available from the literature are those published in [17 - 20]. They give a detailed description of the radiative heat exchange between the pairs of objects gas - wall, wall - material and gas - material. The mathematical interpretation of the complex transmission processes in the considered aggregates created by the author of [21] deserves special attention. It is caused by the fact that this model, unlike those mentioned so far, is not explicitly tailored to a particular technology or specific system. Therefore, it is able to simulate processes in both directly and indirectly heated facilities.

The following important aspects from an engineering point of view must be taken into account when designing rotary kilns. These are:

- the heat transfer,
- the movement of the material through the cylindrical working space,
- the mass transfer between gas and solid phase, and
- the chemical reactions [2].

Although each of these transfer processes has its own specifics and is in itself an interesting enough problem to study, and also has a significant impact on others, it has been argued that heat transfer has priority over other phenomena.

Due to their large size, rotary kilns are often installed on open areas within the industrial sites to whose equipment they are included. Variable weather conditions can have an essential effect on the energy flow that leaves the cage of such a unit. It dissipates uselessly in the environment, which is accepted as a reason to be widely characterized as “heat loss”. This concept contains some conditionality, because according to the law of conservation of energy, it can not be created and disappear, but is transformed from one species to another. Nevertheless, the convenience of expression it offers has led to its use in the forthcoming statement.

The aim of the present article is to analyze the results obtained from calculating the heat loss from a rotary kiln to the surrounding outside air at a typical for latitude and climatic features of Bulgaria average annual temperature and the presence of relatively weak constant wind.

EXPERIMENTAL

From the formulation of the purpose of the work it is clear that a value of the average annual outdoor air temperature has to be selected, which should be typical for the location of Bulgaria and the specifics of its climate.

According to [22], the average annual temperature readings in the plains, where industrial objects applying rotary kilns are usually located, are 11°C - 12°C in the north and up to 14°C in the south.

For the needs of the present study, the value of the average annual temperature in Bulgaria is assumed 12°C (285 K). In order to consider a relatively less favorable option, it is closer to the lower of the specified limits and would accordingly increase the results obtained in the calculations for the heat loss from the tube rotary kiln under discussion.

Quite expectedly, the cited source does not indicate average wind velocity and prevailing direction. With regard to ambient air mobility, the need for long-term monitoring of the settlement in question must be emphasized to have reliable averaged data. They are usually depicted in a diagram with polar coordinates, called the "wind rose" for a given region, expressing in per cents the recurrence of wind in directions, as well as cases of its complete absence, i. e. of "quiet" weather. In order to make it possible to take into account also its speed, in this form of presentation additional sectors are drawn, in which intervals of values of its speed, w_w, $m \cdot s^{-1}$ are marked with different colors.

In this case, strictly defined region and location of the site of the respective enterprise are not considered, therefore a sufficiently representative air flow velocity of 2 $m \cdot s^{-1}$, typical for practically quiet weather could be chosen. In addition, again due to the lack of specifics, the above-mentioned presence of a prevailing wind direction also cannot be considered as a parameter in the study. Instead, it will be assumed that the air flow always blows transversely to the cylindrical cage, i. e. it moves perpendicular to its longitudinal axis, in the horizontal direction. The introduction of such a premise obviously does not correspond to the real situation and contradicts the idea of creating the mentioned wind rose, but is done again in order to consider a less favorable option, so as to obtain an increased value of heat loss from the rotary kiln.

Other climatic factors such as the intensity of solar radiation and the amount of precipitation will not be taken into account for now. On the one hand, they are even more difficult to summarize without specifying the concrete region or settlement, and on the other hand - their impact on the studied object is significantly weaker. In addition, in some cases, especially when the facilities in question have smaller dimensions, canopies can be built over them, which eliminate the influence of these factors.

As an object of study is treated the shown in Fig. 1 tube rotary kiln with direct heating of the material by means of a burner installed in its interior space against the direction of movement of the solid-state filling to be treated [21]. In this case, the heat flow to the inner surface of the cylindrical steel casing is transmitted by the flame, the flue gas, the bulk material bed and the refractory brickwork. It then passes through its wall and is dissipated from the outside towards the surrounding atmosphere.

The mechanisms for heat transport from the outer surface of the practically horizontal cylinder (the angle of inclination can be neglected) to the environment are heat transfer (convection) and emitting (radiation). The mathematical apparatus proposed in [23] was used to determine the coefficients characterizing them.

In Table 1 are systematized the most important indicators of the studied facility and the main climatic factors, which are input data for the implementation of the heat-technical calculations.

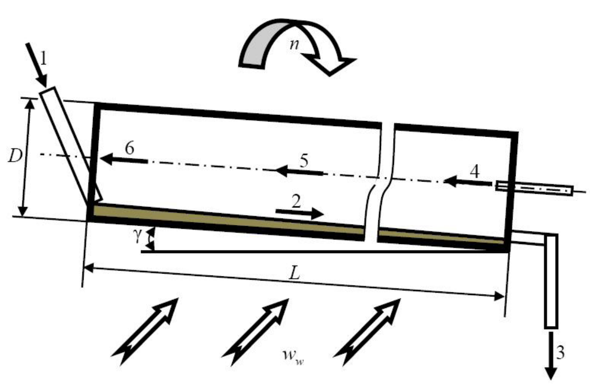

Fig. 1. Movement of the individual media along the schematic longitudinal section of the tube rotary kiln: 1 - raw solid material; 2 - axial flow of solid material through the kiln; 3 - finished solid material; 4 - flame of the burner; 5 - products of burning; 6 - flue gas from the kiln.

Table 1. Data for the considered unit and the most important climatic indicators.

No	Indicator	Symbol	Measure	Value/Explication
1	Type of the unit	-	-	tube rotary kiln
2	Mode of heating	-	-	indirect, with a burner, mounted inside, along its longitudinal axis
3	Energy carrier	-	-	natural gas
4	Motion scheme of the solid material and the flue gas	-	-	counter-current flow
5	Technological purpose	-	-	calcination of limestone
6	Mode of placement on the industrial land	-	-	outdoors, without an awning or other protective equipment
7	Length of the cylindrical cage	L	m	40
8	Radius of the cylindrical cage	R	m	1.4
9	Diameter of the cylindrical cage	D	m	2.8
10	Angle of the inclination of the longitudinal axis relative to the horizontal plane	γ	°	1
11	Average temperature of the outer surface of the cylindrical wall	T_{wall}	K	673
12	Average annual temperature of the outdoor air	T_{air}	K	285
13	Wind velocity	w_w	$m \cdot s^{-1}$	2
14	Mode of flow of the cylindrical cage by the wind	-	-	transverse, in a horizontal direction
15	Condition of the outer surface of the steel cylindrical wall	-	-	corroded

RESULTS AND DISCUSSION

Table 2 depicts the values of heat transfer coefficients calculated by the method proposed in [23], from the outer surface of the wall of the tube rotary kiln to the surrounding space in the presence of only natural convection (α_n), only forced one ($\alpha_f^{w_w=2\ m \cdot s^{-1}}$), a combination of the first two types of convection ($\alpha_c^{w_w=2\ m \cdot s^{-1}}$), by radiation ($\alpha_r$), as well as the total heat transfer coefficient in the absence of wind ($\alpha^{w_w=0\ m \cdot s^{-1}}$) and that taking into account all the mechanisms listed so far ($\alpha^{w_w=2\ m \cdot s^{-1}}$).

Comparisons between the shares of the obtained heat transfer coefficients, characterizing the heat loss from the tube rotary kiln, in the total value of this indicator in the absence of wind, are shown in Table 3.

Table 4 offers similar information, but in the presence of a constant wind with a velocity of 2 $m \cdot s^{-1}$.

Based on the presented in Tables 2 - 4 data, an analysis of the contribution of the individual components in the total heat transfer coefficient from the cylindrical cage to the surrounding space can be performed. It shows on the one hand that at the chosen relatively low wind speed, the radiative heat exchange is about 2.8 times more intense than that by convection.

In addition, the comparison of the heat transfer coefficient caused only by natural convection, i. e. in absolutely quiet weather, with that conditioned by the forced one due to the constant transverse wind with a velocity of 2 $m \cdot s^{-1}$, amounting to 7.375 $W \cdot m^{-2} \cdot K^{-1}$ and 6.384 $W \cdot m^{-2} \cdot K^{-1}$, shows the low intensity of the second mechanism, leading to even a lower (albeit insignificant) level of the indicator characterizing it. The value of the total coefficient of convective heat transfer is 8.244 $W \cdot m^{-2} \cdot K^{-1}$, which is fully comparable with the already mentioned its two components, due to natural and forced convection.

Fig. 2 illustrates the information proposed in Table 2

Table 2. Heat transfer coefficients at different conditions.

Indicator	α_n	$\alpha_f^{w_w=2\ m\cdot s^{-1}}$	$\alpha_c^{w_w=2\ m\cdot s^{-1}}$	α_r	$\alpha^{w_w=0\ m\cdot s^{-1}}$	$\alpha^{w_w=2\ m\cdot s^{-1}}$
Value, $W\cdot m^{-2}\cdot K^{-1}$	7.375	6.384	8.244	23.213	30.588	31.457

Table 3. Shares of the separate heat transfer coefficients at absence of wind.

Indicator	$\frac{\alpha_n}{\alpha^{w_w=0\ m\cdot s^{-1}}}$	$\frac{\alpha_r}{\alpha^{w_w=0\ m\cdot s^{-1}}}$	checksum
Value, -	0.2411	0.7589	1.0000

Table 4. Shares of the separate heat transfer coefficients at wind with velocity 2 $m\cdot s^{-1}$.

Indicator	$\frac{\alpha_n}{\alpha^{w_w=2\ m\cdot s^{-1}}}$	$\frac{\alpha_f^{w_w=2\ m\cdot s^{-1}}}{\alpha^{w_w=2\ m\cdot s^{-1}}}$	$\frac{\alpha_c^{w_w=2\ m\cdot s^{-1}}}{\alpha^{w_w=2\ m\cdot s^{-1}}}$	$\frac{\alpha_r}{\alpha^{w_w=2\ m\cdot s^{-1}}}$	checksum from the two previous columns
Value, -	0.2459	0.2029	0.2621	0.7379	1.0000

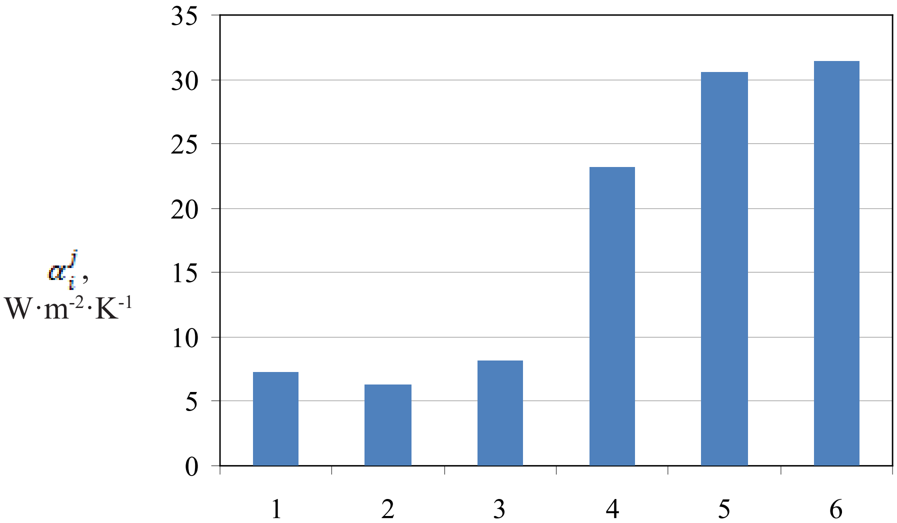

Fig. 2. Comparison between the obtained heat transfer coefficients, denoted by the common symbol α_i^j, $W\cdot m^{-2}\cdot K^{-1}$: 1 – α_n; 2 – $\alpha_f^{w_w=2\ m\cdot s^{-1}}$; 3 – $\alpha_c^{w_w=2\ m\cdot s^{-1}}$; 4 – α_r; 5 – $\alpha^{w_w=0\ m\cdot s^{-1}}$; 6 – $\alpha^{w_w=2\ m\cdot s^{-1}}$.

about the operation of the considered unit.

This diagram confirms the found based on Tables 2 - 4 trends in the behavior of the coefficients characterizing the heat loss from the investigated tube rotary kiln.

Before proceeding to the assessment of the heat flux dissipated through the outer surface of the discussed unit in real conditions, its value will be calculated in case of complete absence of wind, $Q_l^{w_w=0\ m\cdot s^{-1}}$, W. This would provide a basis for comparison and consideration of the impact of this factor.

The determination of the introduced indicator is carried out according to Newton's law:

$$Q_l^{w_w=0\ m\cdot s^{-1}} = \alpha^{w_w=0\ m\cdot s^{-1}} \pi D l (T_{wall} - T_{air}), \quad (1)$$

where π=3.1429 is the Ludolph's number and the coefficient $\alpha^{w_w=0\ m\cdot s^{-1}}$ is calculated by the dependence:

$$\alpha^{w_w=0\ m\cdot s^{-1}} = \alpha_c^{w_w=0\ m\cdot s^{-1}} + \alpha_r = \alpha_n + \alpha_r =$$

$$= 7.375 + 23.213 = 30.588\ W\cdot m^{-2}\cdot K^{-1}. \quad (2)$$

It should be noted that the two bottoms (respectively bases) of the cylinder are in contact with the drive mechanism of the furnace, as well as with the loading and unloading devices for the processed bulk solid material, so that heat loss through them can be neglected (i. e. these two surfaces are considered to be well insulated).

After substitution of the geometric parameters according to Table 1 in (1), is obtained:

$$Q_l^{w_w=0\ m\cdot s^{-1}} = 30.588 \cdot 351.86(673 - 285) =$$

$$4175924.8\ W \approx 4176\ kW. \quad (1')$$

Assuming that the natural gas used as energy carrier in the rotary kiln has a lower specific calorific value Q_{low} = 47000 kJ·kg^{-1} [23] and a density ρ=0.78 kg·m^{-3} [21], and its volumetric flow velocity to the burner covering only this ideally low heat loss is denoted by $B_l^{w_w=0\ m\cdot s^{-1}}$, m^3·s^{-1}, then the latter indicator is defined so:

$$B_l^{w_w=0\ m\cdot s^{-1}} = \frac{Q_l^{w_w=0\ m\cdot s^{-1}}}{Q_{low}\rho} = \frac{4176}{47000\cdot 0.78} = 0.11391\ m\cdot s^{-1}. \quad (3)$$

At first glance, the result obtained seems modest, but with a continuous production cycle of the industrial object, it corresponds to an annual consumption of fuel used for this purpose, amounting to: 0.11391·3600·24·365=0.11391·3600·8760=3592266 m^3.

Given the observed dynamics of the energy market, it is difficult to forecast the average annual price of natural gas. However, as a relatively representative and with a certain amount of optimism for a quick disappearance of the extremes from the beginning of 2022, one in the amount of 110 EUR/1000 m^3 can be considered.

Therefore, covering only this item from the actual heat loss from the furnace for one year would cost the enterprise EUR 395150.

The determination of the heat flux $Q_l^{w_w=2\ m\cdot s^{-1}}$, W, which is dissipated through the outer surface of the wall of the tube rotary kiln to the surrounding space under real conditions, characterized by a weak but constant wind with a velocity of 2 m·s^{-1}, which also causes forced convection, is carried out by a formula analogous to (1), taking into account the presence of the mentioned factor for cooling the unit:

$$Q_l^{w_w=2\ m\cdot s^{-1}} = \alpha^{w_w=2\ m\cdot s^{-1}} \pi D l (T_{wall} - T_{air}) \quad (4)$$

Substituting the numerical values of the participating parameters on the right side of the above expression leads to:

$$Q_l^{w_w=2\ m\cdot s^{-1}} = 31.457 \cdot 351.86(673 - 285) =$$

$$4294562.4\ W \approx 4295\ kW. \quad (4')$$

The repetition of the already used algorithm in the actual situation under consideration leads to an annual operating cost to cover the real heat loss in the present case in the amount of EUR 406424.

This sum is comparable, but expectedly higher than the one obtained above in the absence of wind. Despite the large scale and financial capabilities of the companies whose technological cycles include the units in question, the established value deserves attention and efforts to reduce by the relevant management teams due to the serious energy and economic effects of such measures.

The environmental impact of the smoke coming out of the furnace should also not be neglected. If typical values are chosen for the volume of the flue gas, releasing on the completely combustion of 1 m^3 from the gaseous fuel at real conditions, V^{fg} = 12.83 m^3·m^{-3} and its carbon dioxide content CO_2 = 9.00 % [15], the volume of this greenhouse gas emitted into the atmosphere in one year proves to be: 3592266·12.83·0.09=4148000 m^3·a^{-1}. Taking into account that the density of this environmentally harmful compound at 273 K is 1.9767 kg·m^{-3} [15], the mass of its annual emission will amount to 4148000·1.9767=8199352 kg·a^{-1} or nearly 8200 t·a^{-1}.

Unfortunately, the rapid and largely uncontrollable development of political processes after the beginning of February 2022, however, reduces the grounds for optimism that global and in particular European energy markets will be able to recover to pre-crisis levels. Without taking into account the extremely high values of the price of natural gas, the analysis of the current situation, trends and prospects for its movement shows that it is much more realistic to accept it as between

7 and 10 times higher than the one introduced as a prerequisite for the above calculations. It is obviously that such an "update" would have the same effect on the final results for the annual operating costs, covering the actual heat losses in the considered case, which would amount to between EUR 2.85 and EUR 4 million. At this realistic-pessimistic option, the amount is already quite impressive and the need for efforts to limit it does not need justification.

The obtained results give grounds for the listed below findings, conclusions and recommendations.

1) The comparison of the heat transfer coefficient caused only by natural convection, i. e. in absolutely quiet weather, with that through the forced one due to the constant cross wind with a velocity of 2 m s^{-1}, amounting to 7.375 $W{\cdot}m^{-2}{\cdot}K^{-1}$ and 6.384 $W{\cdot}m^{-2}{\cdot}K^{-1}$, respectively, shows the limited intensity of the second mechanism, leading to even a lower (albeit insignificant) level of the characterizing it indicator.

2) The total convective heat exchange coefficient has a value of 8.244 $W{\cdot}m^{-2}{\cdot}K^{-1}$, which is fully comparable with the already mentioned two components due to natural and forced phenomena.

3) The analysis of the contribution of the individual ingredients in the total heat transfer coefficient from the cylindrical cage to the surrounding space shows that at the chosen relatively low wind velocity, the share of radiation is about 2.8 times higher than that provided by convection.

4) The annual operating costs of the studied unit, aimed at covering the real heat loss from its external surface to the environment, taking into account the main climatic factors, exceed EUR 400000 at relevant for the recent past and reduced current prices.

5) To improve the energy, environmental and economic efficiency of the tube rotary kiln, it may be recommended to limit the serious heat loss through convection and radiation from the outer surface of its metal cage by lowering its temperature and emissivity. This is to be achieved by improving the thermal insulation between the innermost refractory layer of the brickwork and the outermost steel casing of the furnace, as well as by applying a light, best silver-gray coating on the latter, as well as its periodic renewal in order to prevent serious corrosion of the surface.

6) Another constant task for the specialists dealing with the design, construction and operation of such high-temperature units should be the optimization of the technological processes carried out in them, to reduce their specific heat consumption, which would directly affect their heat loss to environment.

CONCLUSIONS

The assessments of heat loss from an industrial tube rotary kiln with direct heating of the material to the ambient air at typical for the latitude and climatic features of Bulgaria average annual temperature and the presence of relatively weak constant wind can be summarized as follows:

- It was found that the intensity of forced convection from the unit cage to the environment at the considered limited wind velocity has a relatively low value, comparable to that due to natural one, as a result of which the total coefficient characterizing their joint influence is comparable in level with its two components.
- It is estimated that under the same conditions the share of radiation is about 2.8 times higher than that provided by convection, which confirms the insignificant contribution of the latter mechanism for heat exchange in heat loss from the considered industrial tube rotary kiln to ambient air and the predominance of emitting.
- The annual operating costs of the unit under study to cover the actual heat loss from its external surface to its surroundings, which exceed EUR 400000, have been determined. They can be reduced by lowering the temperature and the emissivity of its metal cage by applying the measures recommended in the present work, which would improve the energy, environmental and economic efficiency of the tube rotary kiln.

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