Modeling the transportation and batching of slurry into a cement kiln

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Abstract. The work discusses a method for constructing a model of a system for slurry transportation and batching into a cement kiln, as well as the structural modifications for the scheme of slurry batcher. The main goal of the developed model is to investigate the reduction in energy consumption by slurry transportation through reduced amount of pumped raw mixture and stabilized feeding of the slurry into the kiln, which can improve the quality of produced clinker. The modeling and study of transient processes in the hydrodynamic system was performed in MATLAB Simulink. The presented model can be used for designing and modeling a system of slurry batching into the cement kiln.

1. Introduction
The improvement of transportation of raw slurry from a slurry tank into a cement kiln is one of important approaches to energy consumption in cement industry [1]. At a real plant, some schemes of slurry batching implement slurry accumulator that, as a rule, contains excess slurry from 15 to 50 percent of its total amount, and the excess slurry returns to the slurry tank under gravity. The amount of excess slurry depends on the number of kilns where it is fed from the accumulator [2]. Due to technical reasons, some of the kilns may be out of operation; however, the total amount of slurry is fed assuming that all the kilns are in operation. The slurry is preliminarily fed from the slurry tank into intermediate accumulating tanks. Then, it is distributed to the kilns, while the excess slurry from the accumulator returns to the slurry tank. This necessitates increased efficiency of slurry batching into the cement kilns [3].

Uneven feeding of the slurry into a rotary kiln, in the case of wet production, might deteriorate the quality of clinker burning, and sometimes even to accidents during clinker burning [4]. The treatise is aimed at the development of an imitation model of slurry transportation hydrodynamic system to design an automatic control system for slurry batcher. This will improve the production control and hence reduce the energy consumption for slurry transportation and increase the production efficiency.

2. Scheme and principle of slurry batcher operation
Let us consider the reduction of energy consumption conditioned by the instability of slurry batching into the kiln on the example shown in Ошибка! Источник ссылки не найден.. The proposed scheme assumes excess slurry transportation control, which will provide constant level in the slurry accumulator. An important thing in the scheme is that the implementation of the suggested method requires no
appreciable modification of mechanical elements of an existing system for slurry feeding into the cement kiln, and hence no considerable expenses.

By design, the slurry transportation system consists of two reservoirs connected by a system of pipes and automation equipment (sensors, actuators). The first reservoir is slurry tank 1, the second one is intermediate stabilizing slurry accumulator 5.

The slurry from first reservoir 1 into second reservoir 5 is moving along the pipeline due to pressure difference at the beginning of the pipeline and at its end created by centrifugal slurry pump 2. In the considered scheme, the pump delivery pipe includes valve 3 that is intended for regulation of slurry feeding rate and estimation during modeling of the impact on slurry movement in the pipeline. Technologically, valve 3 is necessary for closing the main pump pipe after engaging backup pump 4, for instance in the case of the failure of the former.

![Diagram of slurry feeding into a cement kiln.](image)

Figure 1. The scheme of slurry feeding into a cement kiln.

From stabilizing reservoir 5 the slurry is fed into a kiln through adjustable pipe elbow 7 equipped by flow meter 8 at its outlet. Supporting constant slurry level in accumulator 5 allows stabilizing slurry flow rate through outlet 7 by maintaining constant slurry head pressure in reservoir 5, which is ensured by continuous filling of reservoirs 5 by feeding excess slurry.

To reduce the excess slurry flow, flow meter 6 is mounted at the slurry return pipe outlet that provides feedback for the pump speed regulator. This provides minimal slurry flow rate. Slurry returns to the slurry tank under gravity. To solve this problem, the considered slurry flow control loop should be equipped with a PID controller.

The considered structure of slurry batcher with a slurry return pipe is used at Russian cement plants implementing wet process. However, the existing schemes do not offer the control of slurry feeding by the pump which would account for excess slurry. Thus, the existing schemes cause unnecessary energy consumption for additional pumping of excess slurry.

Interestingly, with constant level in intermediate reservoir 5, the feeding of slurry without its return is problematic due to possible fluctuations of the pump [5]. Considering that cement plants use the scheme with slurry return and, for the studied variant, small volume of the intermediate stabilizing reservoir, to model slurry feeding into the cement kiln, we selected the hydrodynamic slurry movement scheme depicted in figure 1.
3. Modeling slurry movement hydrodynamics

For the hydrodynamic design of the piping system, we will derive mathematical models of separate elements with their further combination into a unified system, hence formulate a generalized model of slurry movement. The slurry tank is a cylindrical reservoir of variable level with one inlet and one outlet pipes; the slurry in the tank is under atmospheric pressure. Slurry movement in the slurry feeding system may cause pressure losses in connecting pipes and the reservoir, i.e. local friction resistance and flow depression resistance occur.

The pressure in every connecting pipe with the reservoir can be determined by the following equation [6]:

\[ p = p_{\text{level}} - p_{\text{loss}} + p_{\text{res}}, \]

where \( p_{\text{level}} \) is slurry head pressure at pipe level, \( p_{\text{loss}} \) is pressure loss in the pipe, \( p_{\text{res}} \) is pressure in the reservoir (since the slurry tank is an open reservoir, then \( p_{\text{res}} = 0 \)).

The slurry head pressure at the level of outlet pipe can be determined as

\[ p_{\text{lev.outlet}} = g \cdot \rho \cdot h, \]

where \( g \) is gravity acceleration, \( \rho \) is slurry density, \( h \) is altering slurry head height above the outlet pipe.

Considering that the inlet pipe is above the outlet one, the slurry head pressure at the level of inlet pipe can be determined as

\[ p_{\text{lev.inlet}} = g \cdot \rho \cdot (h - h_B), \]

where \( h_B \) is the height of the slurry head between the inlet and outlet pipes.

In general, the equation of the slurry volumetric flow rate through each pipe can be expressed as

\[ q = \sqrt{\frac{2}{\rho}} \cdot \frac{p_{\text{crit}}}{\left(p_{\text{crit}} + p_{\text{out}} \right)^{1/2}}, \]

where \( K \) is the coefficient of pressure loss during slurry movement into the pipe and from it; \( S \) is the pipe cross-section area; \( \rho \) is slurry density; \( p_{\text{crit}} \) is critical pressure at which slurry transits from laminar flow into turbulent one and that can be calculated as

\[ p_{\text{crit}} = K \cdot \left( \frac{\text{Re}_{\text{crit}} \cdot \nu}{d} \right)^2, \]

where \( d \) is pipe diameter, \( \nu \) is slurry movement rate, \( \text{Re}_{\text{crit}} \) is critical Reynolds number, which will be assumed to be equal to 15.

To study the dynamics of slurry movement in the system let us assume the variable slurry volume in the intermediate reservoir depending on time \( t \). Thus, the volumetric slurry flow rate can be determined as

\[ V(t) = V_0 + (q_{\text{in}} - q_{\text{out}}) \cdot t, \]

where \( V_0 \) is the initial slurry volume at initial moment of time, \( q_{\text{in}} \) is volumetric slurry flow rate at the reservoir inlet, and \( q_{\text{out}} \) is volumetric slurry flow rate at the reservoir outlet, \( t \) is time.

The considered equations for the slurry tank can be also used for the slurry movement dynamics in the intermediate reservoir.

Let us consider the part of the hydraulic system including the centrifugal pump. Evidently, the main characteristic of a pump is its head curve, i.e. the dependence of the pump head on the flow rate \( H-Q \) (P-Q), as well as dependence of the pump power output on the flow rate \( N-Q \). Both characteristics are considered at a given pump rotation speed with due consideration of a given slurry density.

The mathematical model of the pump can be realized by approximating the factory characteristics of a specific pump. In particular, to calculate pressure created by the pump with a due account for the pump rotation speed, the law of similarity can be used:

\[ p = p_0 \left( \frac{\omega \cdot \rho}{\omega_0 \cdot \rho_0} \right)^2, \]

where \( p_0 \) is pressure set in the P-Q characteristic, \( \rho_0 \) is slurry density for which the P-Q characteristic was set, \( \omega_0 \) is pump rotation speed for which the P-Q characteristic was set.

The volumetric flow rate of the pump can be calculated for the following expression of similarity:
0 = \frac{\partial \rho}{\partial \rho_0} q.

Similarly to the building up pressure, the pump output power can be calculated as

\[ N = N_0 \left( \frac{\alpha}{\rho_0} \right)^{\frac{1}{3}} \frac{\rho}{\rho_0}. \]

During modeling of the slurry movement in the pipeline, one should consider the head losses during slurry movement in the whole pipeline caused by friction resistance, local resistances, such as pipe elbows, unexpected contractions and expansions of pipes [7].

In the developed model, the equation for determination of total pressure loss at the pressure section of the pipeline \( p_{\text{loss}} \) can be expressed as

\[ p_{\text{loss}} = p_v + 2 \cdot p_E + p_{FR}, \]

where \( p_v \) is head loss in the valve, \( p_E \) is head loss in pipe elbow, \( p_{FR} \) is friction head loss along the whole pipeline.

Pressure losses in the pipe elbow are calculated using the coefficient of pressure losses that is usually present in catalogs, manuals or corresponding guide books.

The equation of pressure loss during slurry movement in the pipe elbow is as follows:

\[ p_K = K_K \cdot \frac{\rho}{2S} q \cdot \frac{\rho}{\rho_0}, \]

where \( K \) is reference coefficient of pressure loss. Let us assume it to be equal to 1.1.

Let us consider a model of a uniform-section tube used to transport a fluid. We are not accounting the compressibility and inertia of the slurry. Water hammer effect is also not considered. The end effects are also not considered, assuming that the flow is completely developed along the whole pipeline.

Since the intermediate reservoir is located above the level of the slurry tank, the model of movement along the pipeline should account for the head pressure of the slurry in the pipeline.

The friction pressure losses are calculated by Darcy’s equation in which the losses are proportional to the coefficient of local resistances and slurry flow rate.

\[ p_{FP} = \frac{\xi v^2}{2g}, \]

where \( \xi \) is the coefficient of local resistance, \( v \) is average slurry flow rate, \( g \) is gravity acceleration.

When shifting from laminar to turbulent regime, the friction coefficient is determined by linear interpolation between extreme points of the regimes. The friction coefficient in turbulent regime is determined by Haaland’s approximations [8].

As a result of accepted assumptions, the pressure losses along the pipeline due to friction and slurry head pressure in the pipe can be described as

\[ p_{FP} = f \left( \frac{L + L_{LR}}{d} \right) \cdot \frac{\rho}{2S} q \cdot |q| + \rho \cdot g (h_{out} - h_{in}), \]

where \( L \) is geometrical pipe length, \( L_{LR} \) is total length of local resistances, \( d \) is hydraulic pipe diameter, \( \rho \) is slurry density, \( S \) is pipe cross-section area, \( q \) is volumetric slurry flow rate, \( g \) is gravity acceleration, \( h_{out} \) is level of pipe end, \( h_{in} \) is level of pipe start.

Coefficient \( f \) is calculated by the equations depending on the Reynolds criterion:
where \( K \) is the coefficient characterizing the pipe shape, \( r \) is the height of roughness on the pipe internal surface, \( f_L \) is the coefficient of laminar boundary friction, \( f_T \) is the coefficient of turbulent boundary friction, \( Re_L \) is maximum Reynolds number for laminar flow, \( Re_T \) is minimum Reynolds number for turbulent flow, \( Re \) is Reynolds number:

\[
Re = \frac{q \cdot d}{\nu},
\]

where \( \nu \) is kinematic viscosity.

Further, let us consider the mathematical description of the valve mounted at the pressure pipe of the pump. The valve is a ball valve with conical seat. The valve is characterized by the ball diameter, cone angle and hole diameter. The flow rate through the valve is proportional to the ball displacement and pressure drop.

The volumetric flow rate through the valve is determined as

\[
q_v = K_v \cdot S(h) \cdot \sqrt{\frac{2}{\rho}} \cdot \frac{p_v}{(p_v + p_{con}^{1/2})^{1/2}},
\]

where \( p_v \) is the pressure drop during the slurry movement through the valve, \( K \) is the coefficient of flow depression, \( S(h) \) is the instantaneous area of the valve port that depends on the valve opening \( h \):

\[
S(h) = \begin{cases} S_1, & h \leq 0; \\ \pi \cdot \cos \frac{\theta}{2} \cdot \sin \frac{\theta}{2} \cdot h(D + \sin \frac{\theta}{2}) h, & 0 < h < h_{\text{max}}; \\ S_0 + S_3, & h \geq h_{\text{max}}, \end{cases}
\]

where \( D \) is the ball diameter, \( \theta \) is the coneical seat angle, \( S_3 \) is the leakage area for closed valve, \( S_0 \) is the cross-section of fully open valve:

\[
S_0 = \frac{\pi \cdot d_0^2}{4},
\]

where \( d_0 \) is the valve hole diameter.

The critical pressure, at which the regime of slurry flow through the valve transits from laminar into turbulent one, can be calculated as

\[
p_{\text{con}} = \frac{2}{\rho} \left( \frac{Re_{\text{con}} \cdot \nu}{K \cdot d_k} \right)^2,
\]

where \( d_k \) is instantaneous hydraulic valve diameter:

\[
d_k = \sqrt{\frac{4 \cdot S(h)}{\pi}}.
\]

Let us determine the parameters of the elements of the developed model.

The modeled fluid is raw slurry that belongs to Bingham fluids with the following average characteristics:

- Density: \( \rho = 1600 \text{ kg/m}^3 \);
- Dynamic viscosity: \( \eta = 0.1 \text{ Pa·s} \);
Kinematic viscosity: \( n = \eta / \rho = 6.25 \times 10^{-5} \).

Further, as an example, let us determine the dimensions for the slurry feeder scheme on figure 1.

The diameter of the slurry tank \( d_t = 20 \) m, the height from the inlet pipe to the return pipe \( h_r = 5 \) m. The horizontal length of the pressure and return pipelines \( L_p = 70 \) m, the height from the slurry level in the tank to the stabilizing reservoir \( h_r = 30 \) m. Finally, the total length of the pipeline in one direction is 100 m.

The diameter of the stabilizing reservoir \( d_s = 1.59 \) m, the slurry height and return pipe height is \( h_s = 2 \) m from the reservoir bottom, while the pipe height that leads from the reservoir bottom to the kiln \( h_k = 1.5 \) m.

Let us consider pump model formulation on the basis of its pressure characteristic that is usually provided by a manufacturer.

Let us choose a horizontal single-casing volute pump 6Sh8-2 (GShN-150/30) with axial input of slurry and asynchronous electric motor. The pump is intended for pumping abrasive hydraulic fluids (clay and gravel solutions, mixtures of water with sand, ore and other) with a density up to 2500 kg/m\(^3\) at a temperature from +5 C\(^\circ\) to +55 C\(^\circ\).

The maximum volumetric flow rate that can be provided by the pump at the head of 30 m and the pump rotation speed of 1500 rpm is 200 m\(^3\)/h (Figure 1). Considering that the maximum slurry flow rate for a single kiln is 60 m\(^3\)/h, the chosen pump can concurrently provide slurry for three kilns.

Let us determine the diameters of pipelines of the developed model for the following sections: pressure section from the slurry tank to the intermediate slurry accumulator, return section from the slurry accumulator into the slurry tank, and the pipe section from the accumulator to the kiln.

![Figure 2. Technical characteristics of the modeled slurry pump 6Sh8-2.](image)

For the given flow rate, the inner pipeline diameter can be calculated by the flow rate equation:

\[
    d = \frac{4 \cdot q}{\pi \cdot \omega},
\]

where \( q \) is slurry volumetric flow rate, \( \omega \) is average slurry flow rate.

The main element on the pressure section is the pump capable of providing maximum slurry flow rate of 0.05 m\(^3\)/s. The velocity of viscous capillary liquids should not exceed 1 m/s, thus
the nearest to 0.264 m diameter of standard steel pipe (as per GOST 10704-91) is 0.273 m.

The ultimate slurry flow rate into the kiln is 0.016 m$^3$/s, while the slurry gravity flow rate is assumed to be 0.8 m/s. Then, the internal diameter will be

$$d_{p.s} = \sqrt{\frac{4 \times 0.055}{\pi \times 1}} = 0.264 \text{ m}.$$  

Then, the pipe diameter as per GOST is 0.219 m.

The flow rate of the return slurry from the accumulator to the slurry tank is also assumed to be 0.55 m/s. The volumetric flow rate will be considered to be close to the flow rate for the slurry pump of 0.04 m$^3$/s with deduction of the slurry flow rate into the kiln for the case of control system failure. Then, the calculated pipeline diameter is

$$d_{p.r} = \sqrt{\frac{4 \times 0.04}{\pi \times 0.55}} = 0.304 \text{ m},$$

while, the pipe diameter as per GOST is 0.325 m.

To provide the feedback on the volumetric flow rate, an electromagnetic flow meter Proline Promag 50W (DN325) is mounted on the return pipe that is capable of detecting the minimal flow rate of 30 m$^3$/h.

Then, let us consider the realization of the model of the slurry transportation system in MATLAB SimHydraulic simulation environment (Figure 3) on the basis of considered mathematical equations [9].

![Hydrodynamic simulation model of control of slurry feeding into a cement kiln implemented in MATLAB Simulink.](image-url)

The hydrodynamic simulation model includes the slurry tank (Variable Head Two-Arm Tank) from which the slurry through the centrifugal pump is fed into the intermediate slurry accumulator (Variable Head Three-Arm Tank). The pipeline model includes local resistances (Pipe Bend) represented by pipe elbows, as well as pipelines themselves (Resistive Pipe LP) with the valve (Ball Valve with Conical Seat). In the return pipeline, a flow meter is mounted (Hydraulic Flow Rate Sensor Return). The characteristics of the modeled slurry are set in component (Custom Hydraulic Fluid) [10].
Let us make a simulation for step-wise impact, i.e. constant pump revolution rate of 1300 rpm. Such reduced rate was conditioned by the possible overflow of the intermediate stabilizing reservoir at nominal pump rotation speed and closed kiln feeding pipe.

Figure depicts the plots of transient processes obtained after modeling, on which 3 stages can be distinguished.

At the first stage up to the 150th second, the filling of the intermediate stabilizing reservoir proceeds. This section should be considered as a transport lag when the slurry feeder is engaged, which should be taken into account during the design of the slurry return control system.

At the second stage up to the 250th second, an aperiodic process of the return pipe filling with slurry occurs.

The third stage of modeling is characterized by slurry feeding into the kiln, which leads to the redistribution of slurry fed into the intermediate stabilizing reservoir in two directions, namely, slurry feeding into the kiln and return of excess slurry fed into the intermediate buffer reservoir from the slurry tank. The buffer reservoir plays stabilizing and distributing functions during slurry feeding both into a specific kiln and into other kilns that are connected to the buffer reservoir.

The intensification of slurry transportation is possible through application of mechanical vibration which positively affects the mobility of the cement slurry. However, such actions have drifting extreme dependencies, for which, a mathematical model of slurry movement was developed in the form of a non-linear dynamic system.

4. Conclusions
The work has suggested a methodology for maintaining a constant level of slurry in the intermediate buffer reservoir by changing the pipe elbow position. The suggested methodology will allow stabilizing the slurry transportation, excluding slurry flow rate and fluctuations conditioned by various factors, for instance, alteration of the feeding rate. It also enables the stabilization of slurry feeding into a kiln and increased quality of the process control and produced clinker. Besides, the suggested scheme of slurry feeder allows decreasing the energy consumption due to decreased amount of slurry returned to the slurry tank.

The modeling results illustrate the dynamics of the slurry feeder behavior. The model allows investigating the transient processes in the hydrodynamic system, including transportation lag during the slurry feeder activation. The developed model can be used as the basis for elaboration of a pump.
rotation speed controller to reduce the amount of slurry returned to the slurry tank. In addition, we proposed a batching pipe control device for stabilization of slurry feeding into a kiln.

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