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Maintenance Of Under Grate Pressure in Grate Coolers Used In Cement Kilns by IMC Based PID Controller

G.Srividhya[1], M.Guruprasath[2], S.Jayalalitha[3]

Undergraduate Student, SASTRA University, Thanjavur, Tamil Nadu, India[1]

Deputy Manager, FLSmidth Pvt Ltd, Chennai, Tamil Nadu, India[2]

Assosiate Dean, Dept of E&I, SASTRA University, Thanjavur, Tamil Nadu, India[3]

ABSTRACT: A design of Internal Model Control based PID controller for maintaining the under grate pressure of a grate cooler used in cement plants is presented in this paper. Under Grate Pressure is the minimum air pressure, required at the grate to penetrate a bed of hot clinker of given thickness and permeability. It is critical to maintain a constant under grate pressure as high pressure causes the clinker to form an unstable state of suspension and low pressure causes heat from clinker to damage the cooler grates. Here, the use of IMC based PID controller overcomes the drawbacks of PID controller such as high response time, delayed response to large disturbances and lack of model knowledge in controller design.

KEYWORDS: IMC based PID controller, grate cooler, Under Grate Pressure (UGP), kiln.

I. INTRODUCTION

In grate coolers, in order to provide proper cooling of clinker, initially there were efforts to measure the temperature of the clinker using thermocouples and then vary the air pressure accordingly. But this was unsuccessful because thermocouples or any other temperature sensing elements could not stand up under normal temperature conditions. It was also difficult to determine the temperature profile of the clinker along the entire length of the cooler. Hence a method of maintaining the under grate air pressure constant by varying the grate speed was introduced. This not only eliminated the use of additional sensing elements but also helped overcome disturbances like kiln load change and speed change. Previously PID controllers were used to control UGP. But they did not effectively respond to changes in speed of the grate and were also slow while responding to large changes in kiln feed.

In cement manufacturing, there are 3 important steps.Mining, grinding and homogenization of raw materials of Limestone, silica, alumina, iron in the raw mill to form “raw mix”. Calcination of calcium carbonate followed by burning in the kiln and the resulting calcium oxide together with silica, alumina, and ferrous oxide at very high temperatures forms “clinker”. The clinker is then ground or milled together with gypsum in the finish mill to produce “cement” which is then stored in huge Cement silos.

Raw mix is sent into the kiln along with fuel and air .70% of air input to kiln comes as combustion air through cooler fans and the rest as pre-heated combustion air from cooler outlet. Kiln provides thermal input to the raw mix by heating it to an optimal temperature of 2200 deg F. At 1200 deg F, calcination is complete and CO_2 is removed ($CaCO_3 \rightarrow CaO + CO_2$). The clinker from kiln is sent to the cooler to reduce its temperature to 100-200 deg F. This is done as hot clinker cannot be directly ground with the finishing product gypsum. In Industries, the most commonly used cooler is the grate cooler. In a grate cooler, a layer of clinker coming from kiln is spread on a more or less horizontal perforated grate, through which cold air is blown by means of cooler fans installed under the grate. The grate is made of steel, and the cold air from cooler fans keeps it sufficiently cool to avoid melting or burning. The clinker from the kiln progresses through the grates of the cooler and the subsequent grates are maintained at higher speeds than the previous ones to prevent accumulation of clinker. This varying speed of the different grates is achieved by using a variable frequency drive. Here the movement of the clinker is approximately at 90 degrees to the air flow from cooler fans, thus making it

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function like a cross-current heat exchanger. A typical grate cooler is 7-8 plates wide and 25-50 plates long (roughly 7-8 ft by 25-50 ft).

The main aim of this paper is to present the IMC based PID controller design to control the under grate pressure despite process disturbance and noise. The disadvantages of using PID are the large response times due to process noise and lag in responding to changes in kiln feed. Use of an IMC based PID control that incorporates the advantages of both IMC and PID controllers eliminate these shortcomings.

II. MODELING OF COOLING PROCESS AND DISTURBANCE PROCESS

The Under grate pressure of the grate cooler is to be maintained at a constant mbar value while the speed of the grate in strokes per minute is varied using a variable speed drive. The grate speed and under grate pressure of the cooler are obtained from the cooler simulator software. They are imported to the system identification tool in MATLAB and a first order plus dead time transfer function of the model is obtained.

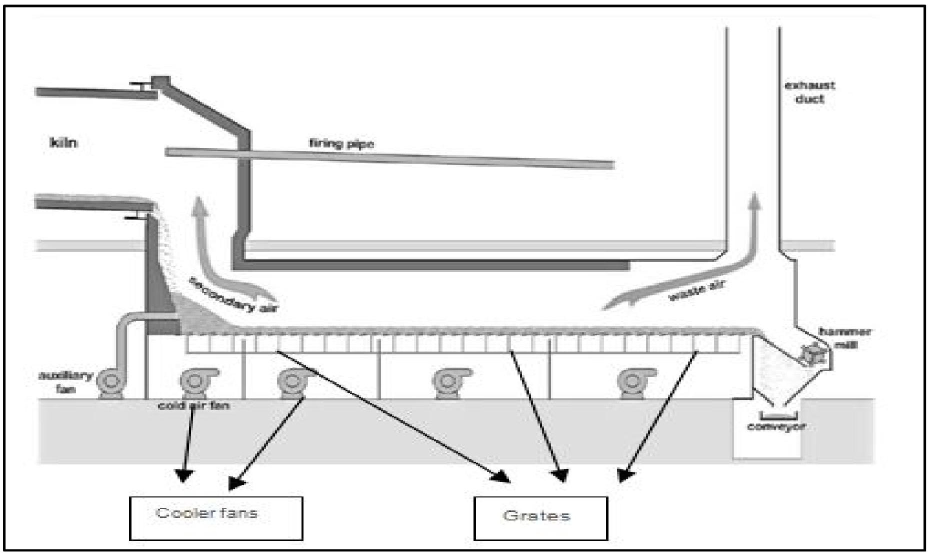

Figure 1- Schematic of a grate cooler

The major disturbance to the cooling process is the unpredictable rate of discharge from the kiln. The change in UGP (in mbar) with change in kiln feed (in tonnes/hr) is also obtained from the cooler simulator software and FOPDT transfer function is estimated for the disturbance process using system identification tool.

Process transfer function

$$\frac{\mathrm{UGP(s)}}{\mathrm{Speed\ of\ grate(s)}} = \exp(-0.0688*s) * \frac{-1.114}{0.8172s + 1}$$

Disturbance transfer function

$$\frac{\mathrm{UGP(s)}}{\mathrm{Load\ to\ kiln(s)}} = \exp(-0.741*s) * \frac{0.0584}{1.605s + 1}$$

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III. IMC BASED PID CONTROLLER DESIGN

Internal model control is a systematic procedure where the knowledge of process model is utilised in designing the control system. The internal model controller consists of a filter term and the inverse of minimum phase term of the process. The output of the IMC controller is given to both the actual process and the model. The difference between the outputs from process and model is compared to the set point and the resulting error is fed as input to the controller.

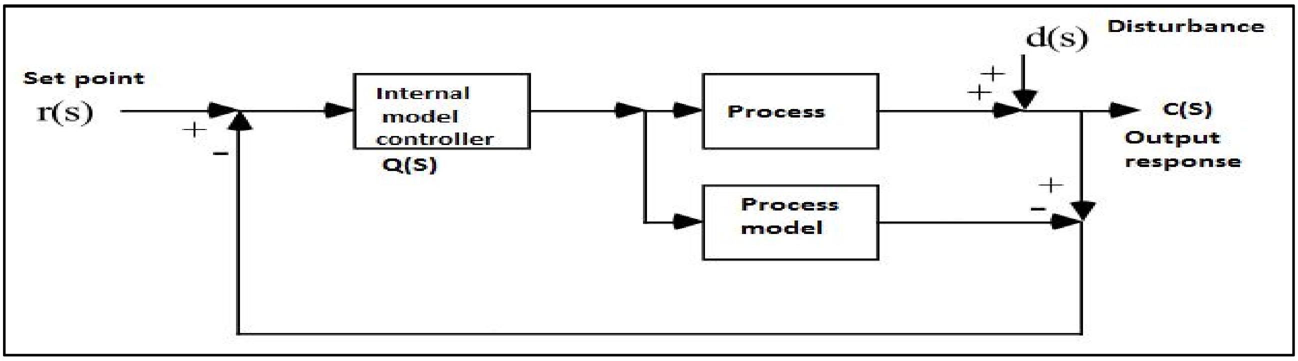

Figure 2 - Internal model control block diagram

The design of Internal model control is complex and the IMC controller is in transfer function form rather than numerical values as in conventional PID controller. Hence by using block diagram reduction techniques, the IMC block diagram is converted to the standard PID form.

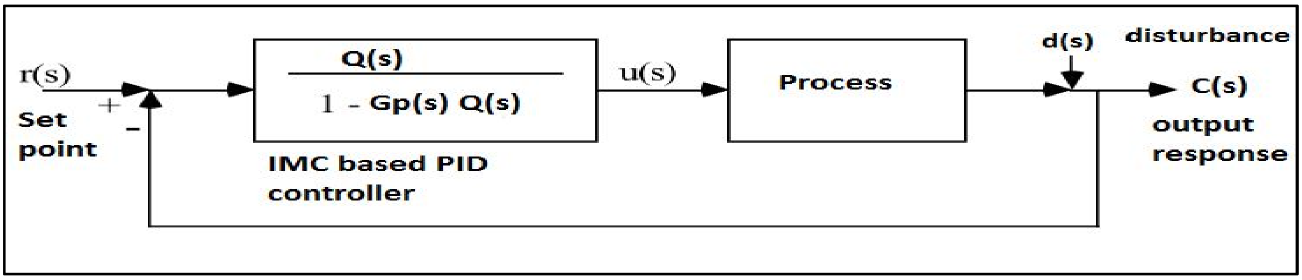

Figure 3 - IMC based PID block diagram

G_p-Process model, K_p-Gain of the process model, T_p-Time constant of the process model, ϴ- Dead time of the process model

Q(s)- Internal model controller, $G_c(s)$- IMC based PID controller

$$G_p(s) = \frac{Kp * e^{-\Theta S}}{TpS+1}$$

The following steps convert the controller to the standard PID form.

Use a first-order Padé approximation for deadtime $\left(e^{-\Theta S} = \frac{-0.5\Theta S+1}{0.5\Theta S-1} \right)$

Hence the process transfer function becomes $\mathbf{G_p(s) = \frac{Kp(-0.5\Theta S+1)}{(TpS+1)(0.5\Theta S-1)}}$

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Separate the non-invertible elements

$$G_{p+}(s) = \frac{Kp}{(TpS+1)(0.5\Theta S-1)}$$

$$G_{p-}(s) = (-0.5\Theta S + 1)$$

The idealized form of IMC controller is $\bar{Q}(s) = \frac{1}{Gp+(s)} = \frac{(TpS+1)(0.5\Theta S-1)}{Kp}$

Filter f(s) is then added. Here, the "derivative" option is used, the numerator of q(s) is allowed to be one order higher than the denominator.

$$Q(s) = \bar{Q}(s)*f(s) = \frac{(TpS+1)(0.5\Theta S-1)}{Kp} * \frac{1}{(\lambda S+1)}$$

Here λ is the filter co-efficient.

The PID equivalent of IMC is $G_c(s) = \frac{Q(s)}{1-Gp(s)Q(s)} = \frac{\bar{Q}(s)*f(s)}{1-Gp(s)\bar{Q}(s)*f(s)}$

$$G_c(s) = \frac{\bar{Q}(s)*f(s)}{1-Gp+(s)*Gp-(s)*Gp-(s)*(1/Gp-(s))\bar{Q}(s)*f(s)} = \frac{\bar{Q}(s)*f(s)}{1-Gp+(s)*f(s)}$$

$$= \frac{1}{Kp}*\frac{(TpS+1)(0.5\Theta S+1)}{(\lambda+0.5\Theta)S}$$

On expanding the numerator term, the following is obtained:

$$G_c(s) = \frac{1}{Kp}*\frac{0.5Tp\theta S^2+(Tp+0.5\theta)S+1}{(\lambda+0.5\theta)S}$$

The above equation is multiplied by $\frac{(Tp+0.5\theta)}{(Tp+0.5\theta)}$ to find the PID parameters.

$$K_c = \frac{(Tp+0.5\theta)}{Kp(\lambda+0.5\theta)} \quad (1.1)$$

$$T_i = (Tp + 0.5\theta) \quad (1.2)$$

$$T_d = \frac{Tp\theta}{2Tp+\theta} \quad (1.3)$$

It is recommended that $\lambda > 0.8\theta$ because of the model uncertainty due to the Padé approximation.

Kp, Tp, θ and λ values are substituted in equations 1.1, 1.2 and 1.3 to find the PID parameters.

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These values are used in the Simulink block diagrams in MATLAB software to get the controller and output responses of the process.

Figure 4 shows the controller output VS time graphs for PID and IMC based PID control system designs from Simulink.

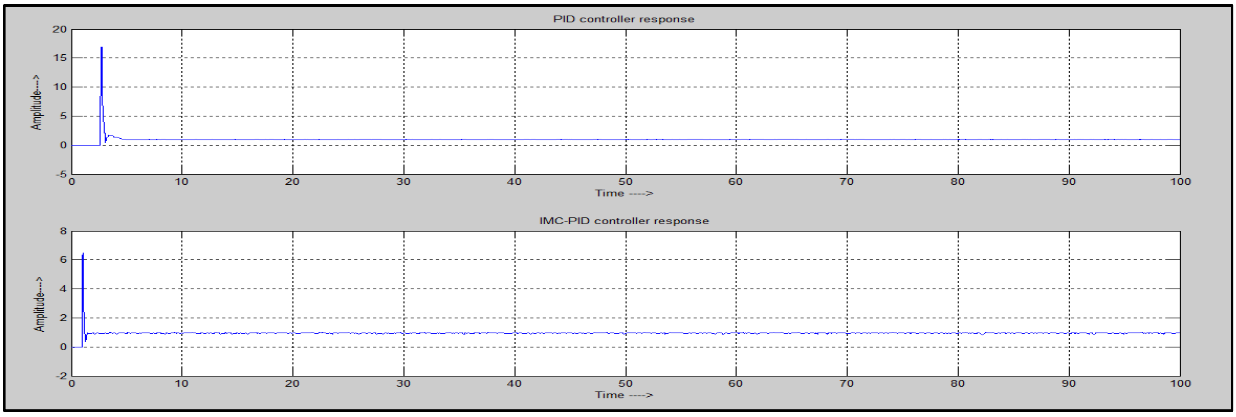

Figure 4 - Comparison of controller response for a step change in set point along with process noise and disturbance

Figure 5 shows the output response VS time graphs for PID and IMC based PID control system designs from Simulink. The below graphs show that the IMC based PID controller has better disturbance rejection and lesser lag while responding to set point and disturbance changes.

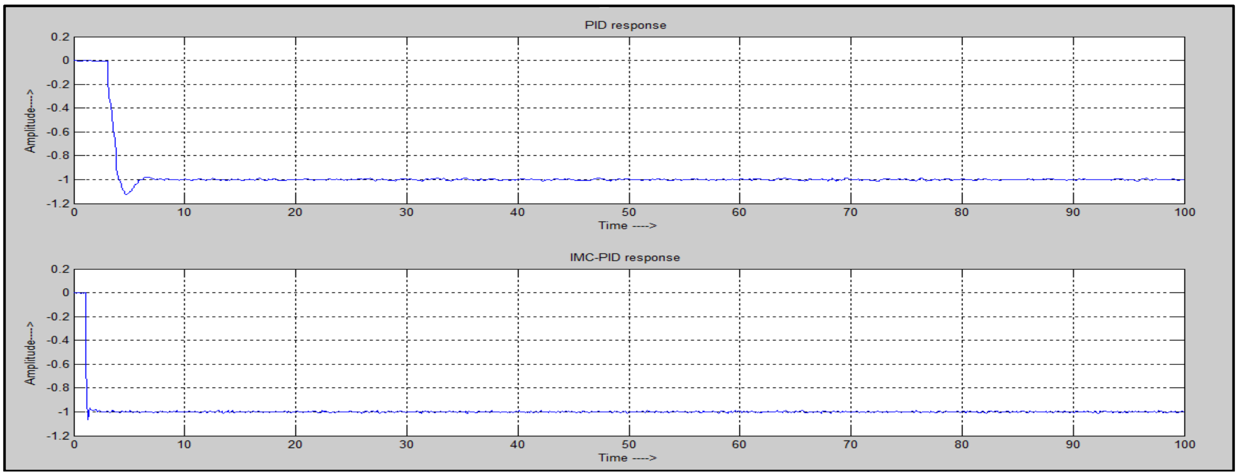

Figure 5 - Comparison of process output response for a step change in set point along with process noise and disturbance

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IV. PERFORMANCE MEASURES

Following Performance measures are error functions used in comparing the quality of controlled responses.

Integral absolute error

IAE = $\int_0^\infty |e(t)|\, dt$

Integral squared error

ISE = $\int_0^\infty \{e(t)\}^2\, dt$

Integral time absolute error

ITAE = $\int_0^\infty t\, |e(t)|\, dt$

For any criterion, the best response corresponds to minimum value of the chosen criterion. IAE is most suitable when digital simulation of the system is used. ISE yields best results for analytical work related to the process. ITAE is usually employed for processes requiring a fast settling time.

Performance measures IAE, ISE, ITAE are found out from the Simulink block diagrams of PID and IMC based PID control systems.

Type of Controller	IAE	ISE	ITAE
PID Control- Kp=-1.5382, Ki=-2.2702, Kd=0.3466			
PID- without disturbance and noise	0.412	0.186	0.809
PID- with disturbance	0.405	0.185	0.793
PID- with noise	0.787	0.189	20.31
PID- with disturbance and noise	0.784	0.188	20.34
IMC based PID Control-Kp=-5.687, Ki=-6.679, Kd=-0.1877			
IMC-PID-without disturbance and noise	0.15	0.109	0.169
IMC-PID- with disturbance	0.157	0.11	0.194
IMC-PID- with noise	0.502	0.112	18.27
IMC-PID- with disturbance and noise	0.472	0.117	16.66

Table 1 –Comparison of performance measures from Simulink block diagrams of PID and IMC based PID controlled processes.

The controller parameters are programmed in the cooler simulator software and the output responses for both PID and IMC based PID controllers are plotted.

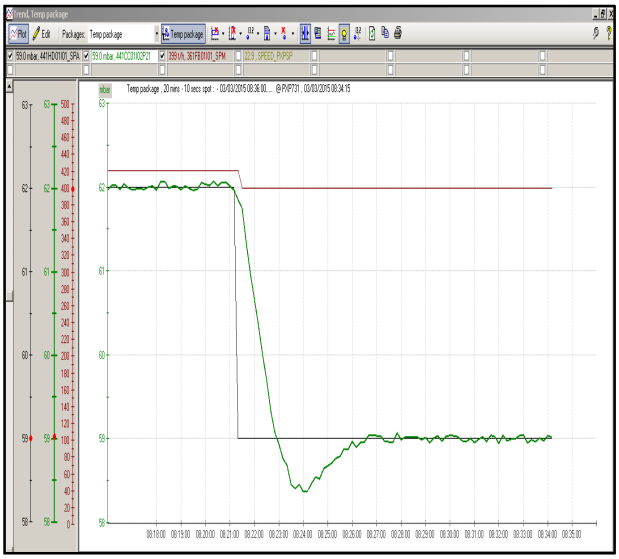

Figure 6 - Process output response from simulator for astep change in set point along with processnoise and disturbance. (PID controller)

Figures 6 and 7 show the output response of the cooling process when it is programmed with PID and IMC based PID controller values respectively.

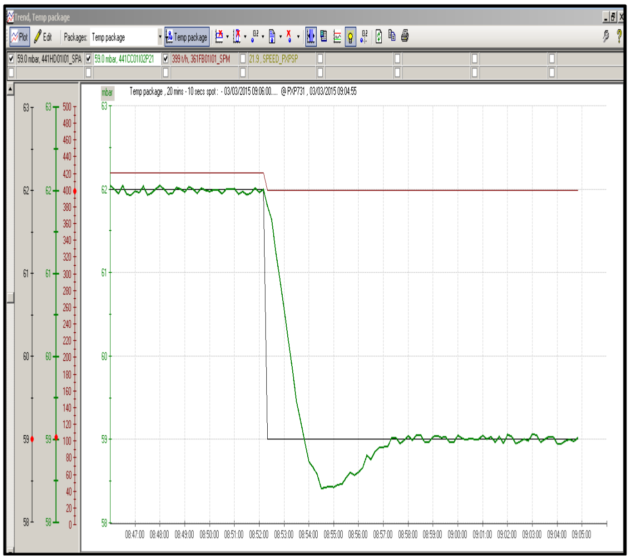

Figure 7 - Process output response from simulator for astep change in set point along with processnoise and disturbance. (IMC based PID controller)

Table 2 lists the performance measures IAE, ISE, ITAE values for PID and IMC-PID outputs. There is a considerable decrease in the performance measure values which indicates the superior performance of IMC based PID design.

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Type of Controller	IAE	ISE	ITAE
PID Control- Kp=-1.5382, Ki=-2.2702, Kd=0.3466			
PID- without disturbance and noise	0.161	0.271	48.215
PID- with disturbance	0.156	0.27	52.11
PID- with noise	0.172	0.272	70.68
PID- with disturbance and noise	0.181	0.297	73.28
IMC based PID Control-Kp=-5.687, Ki=-6.679, Kd=-0.1877			
IMC-PID-without disturbance and noise	0.147	0.23	44.08
IMC-PID- with disturbance	0.143	0.258	46.66
IMC-PID- with noise	0.16	0.262	57.65
IMC-PID- with disturbance and noise	0.174	0.287	48

Table 2 –Comparison of performance measures of PID and IMC based PID controlled processes from cooler simulator software.

V. CONCLUSION

The IMC based PID controller presented in this paper yields better results than the conventional PID controller. There is a significant decrease in the performance measures indicating better performance of the IMC based PID controller. Eventhough the tests indicate better performance of the designed controller compared to PID controller, there maybe few errors due to process-model mismatch. If the closeness of the model to the process can be estimated , it can be incorporated in the controller design to achieve far superior performance. Hence future work needs to be done to investigate the effects of process-model mismatch.

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