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Mathematical Modelling of Energy Recovery of Rotary Kiln and Forecasting of Co_2 Emission in the Indian Cement Industry

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Abstract:- This paper builds up energy balance for the Malabar Cement Plant Palakkad, Kerala, India and estimates the power that can be generated from the waste heat streams. The waste heat from the exhaust gas from the kiln and air discharge from the cooler is recovered by a waste heat steam generation unit (WHRSG). The steam then is used to power the steam turbine driven electrical generator. The electricity generated would offset a portion of the purchased electricity, thereby reducing electrical demand. The energy saved by using the waste heat recovery system is calculated as $8*10^6$ kWhr/yr. The simple payback period of the system is calculated as 18 months. By providing a secondary stationary shell on the kiln surface, the heat loss due to radiation and convection reduces significantly. Forecasting of the CO_2 emission is carried using the system dynamics model. Emission for a period of 20 years from 2010 onwards is forecasted using the software 'Powersim Studio 7'. Projection is done for a period of 20 years from 2010 onwards to 2030. The significance of energy recovery can be shown by forecasting the CO_2 emissions with and without the energy recovery options applied to the system.

I. INTRODUCTION

Energy use in the industrial sector is responsible for approximately one third of the global carbon dioxide (CO2) emissions. In India, six industries have been identified as energy-intensive; they are aluminium, cement, fertilizer, iron and steel, glass, and paper [1]. The cement sector holds a considerable share within these energy intensive industries. The CO2 emissions from cement plants are next only to the coal based thermal power plants. On the global scale the cement industry is responsible for 20% of the manmade CO2 emissions. This contributes to around 10% of the man-made global warming potential

In cement making, nearly half of the carbon dioxide emissions result from energy use and the other half from the decomposition of calcium carbonate during clinker production. Cement is often considered a key industry for a number of reasons. To begin with, cement is an essential input into the production of concrete, a primary building material for the construction industry. Due to the importance of cement for various construction-related activities such as highways, residential and commercial buildings, tunnels and dams, production trends tend to reflect general economic activity.

Globally, over 150 countries produce cement and/or clinker, the primary input to cement. In 2001, the United States was the world's third largest producer of cement (90 million metric tons (MMt)), behind China (661 MMt) and India (100 MMt) [14].

Industrial sector energy consumption varies from 30% to 70% of total energy used in some selected countries as reported in the literatures. A sizeable amount of energy is used in manufacturing cement. Therefore focus should be given on the reduction of energy and energy related environmental emissions locally and globally. It was reported that this segment of industry consumed about 12% of total energy in Malaysia and 15% of total consumption in Iran. Being an energy intensive industry, typically the cement of industry accounts for 50–60% of the total production costs. Thermal energy accounts for about 20–25% of the cement production cost. The typical electrical energy consumption of a modern cement plant is about 110–120kWh per tonne of cement. The main thermal energy is used during the burning process, while electrical energy is used for cement grinding. [18]. World demand for cement was 2283 million tonnes in 2005 and China accounted for about 47% of the total demand. It is predicted that the demand will be about 2836 MT in the year 2010. China will increase its demand by 250 million tonnes during this period. This increase will be higher than the total annual demand for European Union. It was reported that Japan and the US, India is the fourth largest cement-producing country in the world. Mandal and Madheswaran reported that production of cement increased from 2.95 million tonnes in 1950–1951 to 161.66 million tonnes in 2006–2007 in India.

Specific energy consumption in cement production varies from technology to technology. The dry process uses more electrical but much less thermal energy than the wet process. In industrialized countries, primary energy consumption in a typical cement plant is up to 75% fossil fuel and up to 25% electrical energy using a dry process Electrical energy is required to run the auxiliary equipment such as kiln motors, combustion air blowers and fuel supply, etc. [19].

II. WHRSG

The most accessible and in turn the most cost effective waste heat losses available are the clinker cooler discharge and kiln exhaust gases. The exhaust gas from the kiln is 360°C and temperature of air discharge from the cooler is 200°C. Both streams would be directed through a waste heat recovery steam generator and available energy is transferred to water via the WHRSG. A schematic is shown in Fig. 2. The available waste energy is such that the steam would be generated. The steam would then be used to power the steam turbine driven electrical generator. The electricity generated would offset a portion of the purchased electricity, thereby reducing electrical demand.

In order to determine size of the generator, the available energy from the gas stream must be found. Once this is determined, an approximation of the steaming rate for a specified pressure found. The steam rate and pressure will determine the size of generator. We assume a reasonable efficiency of 85% for the steam generator. As the gas passes through the WHRSG, energy will be transferred and gas temperature will drop. Targeting a pressure of 8 bar at the turbine inlet, the minimum steam temperature at the WHRSG exit would be higher the corresponding saturation temperature which is roughly 170°C. After exiting the WHRSG, the energy of these streams can be recovered by using a compact heat exchanger. Hence the final temperature can be reduced as low as possible, which might be limited by the acid dew point temperature of stream. According to the final temperature of both the streams, the final enthalpies have been calculated to be h_{air}=173kJ/kg, h_{eg} =175kJ/kg

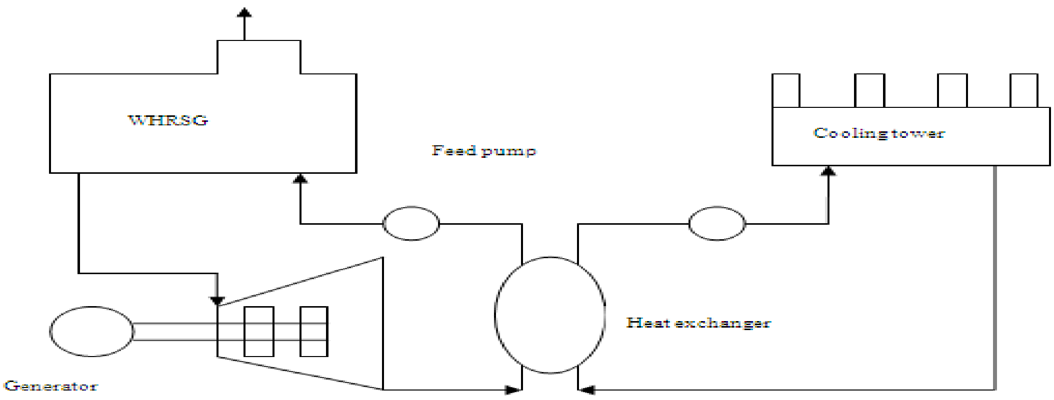


Fig.1. WHRSG APPLICATION

III. FORECASTING OF CEMENT PRODUCTION AND CO_2 EMISSION

A. SYSTEM DYNAMICS MODEL FOR CEMENT SECTOR

In a system dynamics model, the simulations are essentially time-step simulations. The model takes a number of simulation steps along the time axis (Anand, 2005). The dynamics of the system are represented by $dN(t)/dt = kN(t)$, which has a solution $N(t) = N_0$ expt(kt). Here, N0 is the initial value of the system variable, k is a rate constant (which affects the state of the system) and t is the simulation time. For the simulations to start for the first time, initial values of the system variables are needed.

In this paper we have adopted the System Dynamics methodology for the calculation and forecasting of CO2 emissions from the cement industry in India. A software package 'Powersim', which is available for system dynamics analysis has been used in developing a model for the cement sector. In the cement production process around 0.97 tonne of CO2 is produced for each tonne of clinker produced. Its distribution is mainly from calcination (0.54 tonne), use of coal and fossil fuels (0.34 tonne) and electricity generation (0.09 tonne). On an average, around 900 kg of clinker is used in each 1000 kg of cement produced. Thus each tonne of cement is associated with 0.873 tonne of CO2 emissions.

B. FORECASTING OF 13 SELECTED CEMENT INDUSTRIES

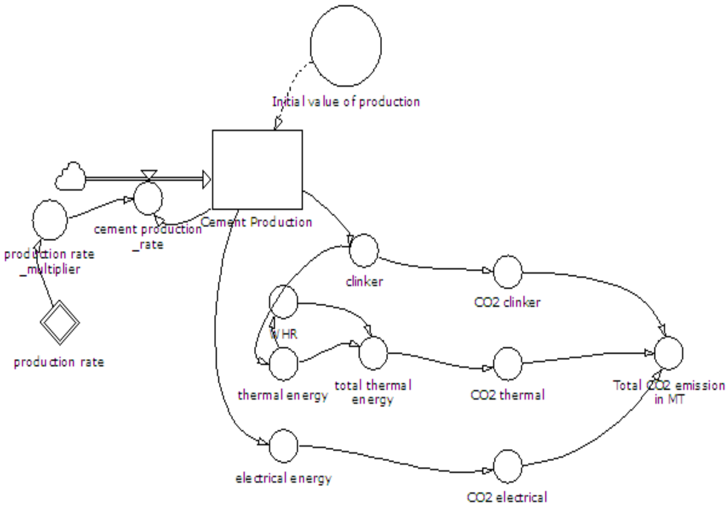
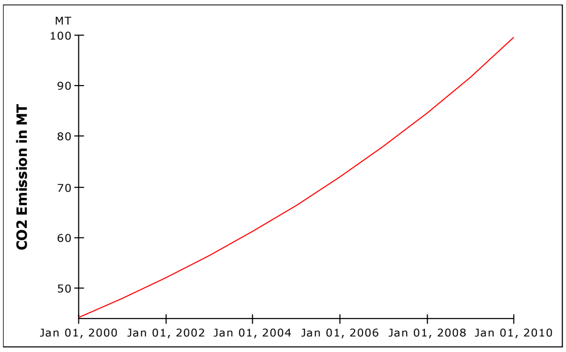


Figure 2. Model for selected cement industries

The above model was developed for the selected 13 cement industries. The model was validated using historical data from 2000 -2010. The cement production growth rates was taken as {8.4}% as the predicted growth rate and {8.8, 19, 4.6, 6.7, 9.8, 8.5, 6.29, 4.5, 10.3}% as the actual growth rate. The results for the same are shown below.

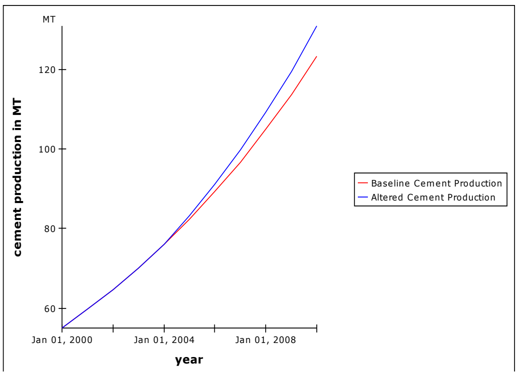
a) Actual Projection

For the historical validation the cement production variable is selected. Data for the year 2000 is incorporated in the model and projections are made up to the year 2010. The model results give good agreement with the actual values, as is shown in the above figure. Points representing the actual and model values of cement production show an overall increasing trend.



Graph 1 Actual Projection

b) Sensitivity Test:

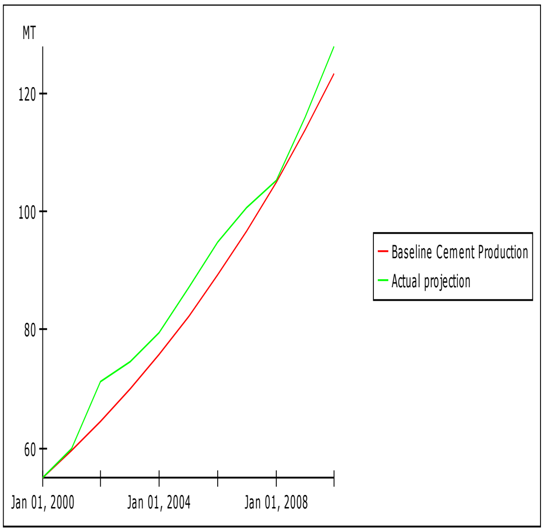


Graph 2 Sensitivity Test

Sensitivity tests basically ascertain whether or not minor shifts in the model parameters can cause shift in the behaviour of the model. Once the robustness of the model is ensured, the model can be used for policy making (Forrester, 1961; Mohapatra et al., 1994). As already discussed, the emissions of CO2 from the cement industry are dependent on population, GDP, cement demand and production.

c) Model Projection:

For the historical validation the cement production variable is selected. The model projection shows the deviation of the predicted cement production from the actual production for 10 years, i.e. from 2000 onwards to 2010. The model results give good agreement with the actual values.



Graph 5: Comparison of the quantity of cement production with the model projections.

C. With Energy Recovery

The model developed for the entire Indian cement industries is shown above. When considering all the Indian cement industries, it is also essential to consider the Indian population, GDP and also the cement demand as all these have a direct influence on the cement production rate. The model is an expanded one from the previouse model shown earlier. This is used to forecast the cement production rate and corresponding CO_2 emission from 2010 onwards to the next 20 years.

D. SCENARIO GENERATION

Here, three scenarios have been considered, each for the population grwoth rate and the cement production growth rate. The first one, being the Baseline Scenario, where the population growth rate is taken as 1.32%, as it was on 2010 and the corresponding cement production growth rate was taken as 8%. The second one, being the S1, the population growth rate is assumed to reduce gradually. In the third scenario S2, the population rate is assumed to reduce gradually and stabilize. For the second scenario in the cement production growth rate, a relation for the cement production rate and population growth rate was developed using least squares method (World Energy-economy scenarios with system dynamics Modeling Carlos de Castro, Luis Javier Miguel, Margarita Mediavilla University of Valladolid Spain). Data from 2000-10 has been used to formulate the relation. Population from 2000 onwards is used to form the growth rate cement demand where the GDP increment rate is 2%(6-8%). The cement production data is used as the Y variable and the growth rate cement demand is the X variable. Interval is 10. and the equation is Y = a + bX, where a & b are positive coefficients. Two switches A & B have been included for the user to select between scenarios. The baseline scenario doesn't employ the energy conservation policies, whereas the scenarios 1 & 2 emply these and a considerable reduction in CO_2 emission can be seen.

The dynamic equations used to account for the baseline scenario (BS), scenario 1 and 2 (S1 and S2) in this subsystems are:

Population = Population + dt * (population growth rate)

where,

population growth rate = conditional population growth rate multiplier * population

Conditional population growth rate multiplier = IF('switch A'=1,

'population BS', IF('switch A'=2,'population s1',IF('switch A'=3,'population s2')))

Population BS = GRAPHSTEP (TIME, STARTTIME,1<<yr>>, population growth rateBS)

Population S1 = GRAPHSTEP (TIME, STARTTIME,1<<yr>>, population growth rate S1)
Population S2 = GRAPHSTEP (TIME, STARTTIME,1<<yr>>, population growth rate S2)
Now, for the cement demand and production, the dynamo equations used in the model are:
Cement demand = cement demand + dt*(cement demand rate)
Cement demand rate = 'growth rate cement demand' * 'cement demand'
Growth rate cement demand = 'conditional population growth rate multiplier' + 'GDP increment rate'
Therefore, Cement demand = Cement demand + dt *{(GDP increment rate + Conditional population growth rate multiplier) *(Cement demand rate)}
Now,
Cement production = Cement production+ dt*(cement production rate)
Where,
Cement production rate = Conditional production multiplier * 'cement production'
Conditional production multiplier = IF ('switch A'=1,'production BS', IF('switch A'=2,'production growth rate based on GDP', IF(switch A=3,production growth rate based on GDP)))
Production BS = GRAPHSTEP (TIME, STARTTIME,1<<yr>>, production growth rate BS)
production growth rate based on GDP = 0.142<<%/yr>>+(2.7611*'growth rate cement demand')
thermal BS = Thermal energy
thermal S1 = 'Thermal energy'-WHR
conditional thermal energy = IF(Conditional production multiplier ='production BS', 'thermal BS',IF(Conditional production multiplier ='production growth rate based on GDP','thermal S1')))
conditional electrical energy conservation = IF(scenario='production S1','elecrical energy S1', IF(scenario='production BS','electrical energy BS',IF(scenario='production based on demand','electrical energy S1')))
electrical energy BS = electrical energy
electrical energy S1 = electrical energy – electrical energy conservation
Total thermal energy = conditional thermal energy
Total CO2 emission in million tones = ('co2 clinker'+'co2 electrical'+'co2 thermal')

a) Baseline Scenario

The rates of population growth cement production rate and GDP as applicable in the year 2010(Performance of Cement Industries, Rajyasabha report) were kept constant for working out the baseline scenarios. The technology employed in making cement was also kept unaltered. Using these options, India's population is projected to reach 1521.64 million by the year 2030. The above graphs and tables show the population growth for the baseline (BS) and scenarios S1 and S2. The cement demand and cement production are also shown. Cement demand projected for the year 2030 by our model is 376.89 million tones.

For the baseline scenarios the model has predicted that in the year 2030, 187.56 Gj of thermal energy and 28.11 GWh of electric energy will be required in the making of cement. The respective CO_2 emissions will then be 173.88, 67.77 and 566.28 million tonnes from thermal energy consumption, electric energy consumption and clinker consumption. The direct CO_2 emissions are estimated to increase from 173.34 million tonnes in the year 2010 to 817.57 million tonnes in 30 years.

b) Modified Scenarios

From the above tables and graphs, it is shown that with the S1 scenario the population of India would reach 1472.10 million in the year 2030. The cement demand will then be 364.85 million tonnes, a reduction of (12.04%)[*] from the base line scenario. To produce the required quantity of cement (1095.11 million tonnes), the consumption of thermal energy will be (219.24) Gj, electricity (32.85) GWh and the clinker requirement will be 843.23 million tonnes. As shown, 944.41 million tonnes of CO2 will be emitted in the year 2030 from a combination of thermal energy consumption, electricity consumption and clinker consumption. A further decrease in all the parameters obviously occurred when we stabilize the rate of population

growth to zero by the year 2025 (S2). With the scenario S2 the population would stabilize at 1392.36 million by the year 2025 and, therefore, remain constant. A reduction of 13.4% (147.1 million tonnes) in cement production is projected for the year 2030 when applying the S2 policy option. Accordingly, the consumption of thermal energy will be 189.79 Gj, electricity use will be 28.44 GWh and 729.98 million tonnes of clinker will be

Figure 3 Model with energy recovery

required. The corresponding CO_2 emissions will be 175.95 million tonnes due to thermal energy consumption, 68.58 million tonnes from electricity consumption, and 573.03 million tonnes in the calcination process. In total a 13.4% (126.84 million tonnes) reduction in direct CO_2 emissions will occur. When we reduce the rate of population growth, a decrease obviously occurs in the cement demand and production. But, the decline in cement demand does not follow the trend of population decrease, as the cement demand is linked to the investment in the cement intensive infrastructure. India being a developing country such an investment will increase.

IV. RESULTS AND DISCUSSION

A. FORECASTING OF SELECTED 13 CEMENT INDUSTRIES FOR 20 YEARS

The projections for the selected 13 cement industries for 20 years is shown in tables 3 and 4 (appendix). From that the following graphs were drawn.

Graph 6

The thermal energy with and without energy recovery option is forecasted for 20 years.
We can see that thermal energy stands at 1470.04 GJ and electrical energy at 20,455.07 kWhr.CO_2 emission is at 725.12 million tones.
Table 12 provides the individual data thermal and electrical energy without energy recovery for each year from 2010 to 2030. We can see that thermal energy stands at 2100.05 GJ and electrical energy at 27273.42 kWhr.CO_2 emission is at 809.97 million tones.

Graph 7

Graph 8

The below table shows the CO_2 emission results from the developed model for 2000-10.

B. COMPARING THE THREE SCENARIOS OF ALL INDIAN CEMENTS WITHOUT WHR

The electrical energy, thermal energy, CO_2 emission, cement production and even cement demand were projected for 20 years and compared for the different scenarios. All the projections were made with and without the energy recovery options applied separately for each of the scenarios and compared.

Graph 10

Graph 11

Graph 12

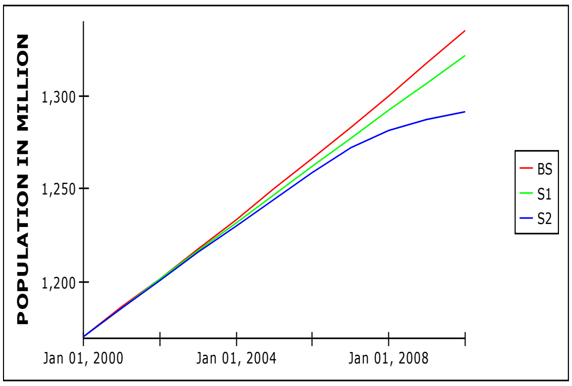
Graph 16

Graph 17

The above graphs compare the cement production, cement demand and CO_2 emission for the three scenarios.

The tables 13-15 (appendix) show the total CO_2 emission, population, cement demand and cement production for the three scenarios considered respectively. From these data, we can see the CO_2 emission corresponding to the cement production and population levels without any energy recovery options applied. Tables 16-18 show the corresponding thermal and electrical energy consumption for each year. From these data, we can see the difference in energy levels under different conditions.

C. COMPARING POPULATION GROWTH RATES



Graph 18

The graph shows the variation of the population curve for the 3 different scenarios considered.

D. COMPARING 3 SCENARIOS WITH WHR

The above tables show the outcome of the energy management policy options for the BS and S1 and S2 scenarios. If 30% thermal energy from the waste heat is taken into account, the CO2 emissions would decline to 915.47, 758.22 and 631.01 million tonnes for the BS, S1 and S2, respectively. The CO_2 emissions would be substantially curtailed by meeting some of the electric energy demand in the cement plants with renewable energy. It is expected that the renewable energy resources will play an important role in the years to come.

Graph 19

Graph 20

Graph 21

From the above graphs, we can compare the reduction in CO_2 emission for the different scenarios. The cement demand and production are obviously linked to the population growth, economic activity in the country, the level and growth of GDP and the level of urbanization. Control of the population growth can be one of the options for mitigating the CO_2 emissions.

As mentioned earlier, we have analysed two scenarios. In scenario 1(S1) the growth rate for population is gradually reduced and in the scenario 2 (S2) a faster decline in the growth rate is analysed where zero growth rate is achieved in the year 2025.

We can see that thermal energy stands at 2373.57 GJ and electrical energy at 30825 kWhr for the baseline scenario. The thermal energy at 1516.22 GJ and electrical energy at 21097 kWhr for S1 and that the thermal energy stands at 1261.85 GJ and electrical energy at 17558 kWhr for S2 scenario.

Graph 22

V. CONCLUSION

Graph 23

Graph 24

The above bar diagrams clearly show the difference in emission levels and energy levels with and without the energy recovery options applied. Hence, this makes us understand the importance of energy recovery to bring down the emission levels and also to reduce the cost of production to a great extent and thereby promise a more greener future to the coming generations. The use of alternate fuels will further help bring down the emission levels but as of now is much more costlier than the conventional fuels. So, more research should be focused on producing cheaper alternate fuels.

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