Development of a Mathematical Model for Continuous Sintering Furnace and its Verification for Performance Evaluation

[#1]Digvijay Gavas, [#2]Anita Nene

[#1]Mechanical Engineering Dept. MIT, Pune, SavitribaiPhule Pune University, Kothrud, Pune-411038, India

Abstract— Sintering continuous furnaces for ferrite products are considerably lengthy and hence heat balance of such furnaces based on bulk assumption is not accurate. Even detailed CFD analysis of such furnace have much higher lead time of analysis. Also, the task becomes tedious when some settings are changed due to change of sintering product requirements. Mathematical model for continuous sintering furnace at Mahindra CIE, Bhosari have developed for performance evaluation. Simulation of mathematical model is carried out using MATLAB script which takes 33 sec to run, facilitating nearly real time analysis. Furnace is divided into differential length and different heat energy paths are calculated. After integration differential heat energy at each location of path it is found that exhaust air losses are 34.5%, the highest losses, following constant shell convection and shell radiation losses, 20.5% and 25.7% respectively. Ferrite product takes 4.3% of energy supplied making furnace thermal efficiency of 4.3%. Mathematical model is verified using measurement of shell temperatures and energy consumption available from factory data. Energy conservation opportunities from are suggested as, to heat recover exhaust air and use it in preheating section of furnace and using 36kW of heat energy lost in cooling zone for green product drying purpose.

***Keywords*:** ferrite, sintering, kiln, MATLAB.

I. INTRODUCTION

Long continuous furnace for sintering process of ferrite is employed in ferrite industry. There are two types of ferrites that are mainly sintered: soft ferrite and hard ferrite. Controlling the required conditions for hard ferrite furnace is relatively simple over soft ferrite furnace. Soft ferrite is critical to conditions inside furnace which has to be of reducing nature to achieved desired properties like power loss. Furthermore, it is necessary to change these conditions as per the various requirement and must be monitored continuously. For this reason a real time system would help in changing the conditions easily and also keep a tab on them. Heat analysis of such furnace using CFD technique to account for furnace flow pattern but renders it a time consuming process (Yukun Hu et al, 2014). CFD problem need to be of steady state nature to reduce its complexity of it and to save computer resource. Hence mathematical model or semi-mathematical model for furnace can solve the problem for lengthy procedure for furnace analysis, also mathematical model can be used as predictive control method for furnace to control proper product qualities.

Various furnace systems are modeled in past, a compartmental furnace model for supercritical coal fired boiler systems is developed by Longzhou Qi et al (2014).Dean A. Lathamp et al (2011) formulate mathematical model for industrial stem-methane reformer. They used mathematical model to calculate combustion gas temperature to maintain tube temperature in furnace, where tube temperature was critical parameter of process as it affects tube life in much greater extent. H. A. J. Vercammen et al (1979) proposed MonteCarlo method to calculate view factor matrix. Also Anton Jacklic et al (2006)used Monte Carlo ray tracing to developed online simulation model with graphical user interface (GUI) for slab reheating pusher-type furnace in Acronid.o.o. in Slovenia. Ali Emadi et al (8-2013) studied heating characteristics of billet walking hearth type reheating furnace, with weighted sum of gray gas model and assuming suitable convective heat transfer coefficient. N. Depree et al (2010) modeled annealing furnace using 3D model and used its information to build highly simplified 1D/2D model.S. Zareba et al (2015) modeled annealing furnace considering radiative and convective heat transfer. Parametric optimization is carried out using nonlinear least square optimization algorithm to estimate optimum value of uncertain parameters like emissivity. Jiin-Yuh Jang et al (2015) modeled walking-beam type reheating furnace for optimizing energy. They showed that energy consumption significantly decrees with decreasing preheating temperature.C.K.Tan et al (2013) have modeled a 200MW reheating furnace using zone modeling, they performed transient 2D simulation showing potential impact on furnace settling time when changing throughput rate to achieve next settling time. In another literature C.K.Tan et al (2014) calculated radiation heat transfer of same furnace using Monte

Carlo ray tracing software REFORM where combustion gas modeled as gray gas. As zone model unable to account for complex flow patterns in furnace, Yukun Hu et al (2015) combined zone model with isothermal-CFD simulation to account these complex flow patterns. Further they showed this simulation model takes about 170 times less time than real process with reasonable accuracies to do supervisory control of temperatures.Yukun Hu et al (2014) zone modeled the walking beam reheating furnace located at Swerea MEFOS, with 1-D and 2-D grid and compare actual run time and computational run time of furnace, concluding computational run is thousand times faster and can be used to real time processing and controlling the furnace.

Radiation heat transfer is dominant phenomena in furnaces making furnace calculation far more difficult due to indications involve in radiation from gray gas. Amount of radiation heat transfer depends on spectrum of radiation, temperature and spectrum dependent absorbity of gas and complex geometric view factors. Simplified gray gas model is used in software simulation with spectral average absorbities making result susceptible to inaccuracies as bad as 23% (PeiyongWang et al, 2014). Further if furnace have electrical heater with normal air as furnace environment clear gas assumption hold good as air contains almost all diatomic non-absorbing gases (Michael Alberti et al, 2014).
Mathematical model were developed for continuous sintering furnace at Mahindra CIE, Bhosari, verified it using factory available data and measurements. Further it is used to analyses performance of furnace

II. **FURNACE DESCRIPTION**

Furnace is sintering continuous type having primarily three zones have length 32 m long (21 number of kilns). Furnace have total 520 kW of electric load connected, out of which 80 kW load is connected in preheating zone (kiln 1-8) where binder is burned off. Remaining 440 kW heaters are in heating zone (kiln 9-16) called sintering zone or soaking zone. Cooling zone is 3rd zone consisting 17-21 kilns, in which kiln 20 and 21 have water cooling jacket. Fig.1 describe schematics of furnace zones and corresponding kiln with position of heaters. Soft ferrite is sintered in this furnace with controlled reducing environment maintained by pouring N_2 gas. Ferrite product is pushed in furnace in two different bunch of tray by a hydraulic actuators. Actuator push these tray for approximately 11.75 min and rest for 2 min making 105 trays pushed per day. Ferrite product remains inside furnace for 24 hours making apparent speed of product as 32 m/day. In preheating zone binder (either water or resins) is burned and get into furnace environment. This binder mixed air is removed from 8 location using a common suction blower of 2280 Nm^3/h capacity. Ambient air enters this zone using 8 air inlet. To maintain reducing environment in sintering phase nitrogen gas is purged in kiln 11 to 16 along with air. To remove air-nitrogen mixed and maintain furnace inside pressure positive (to mitigate infiltration) three blowers of 1320 Nm^3/h, 1320 Nm^3/h and 405 Nm^3/h capacities are provided in heating zone.

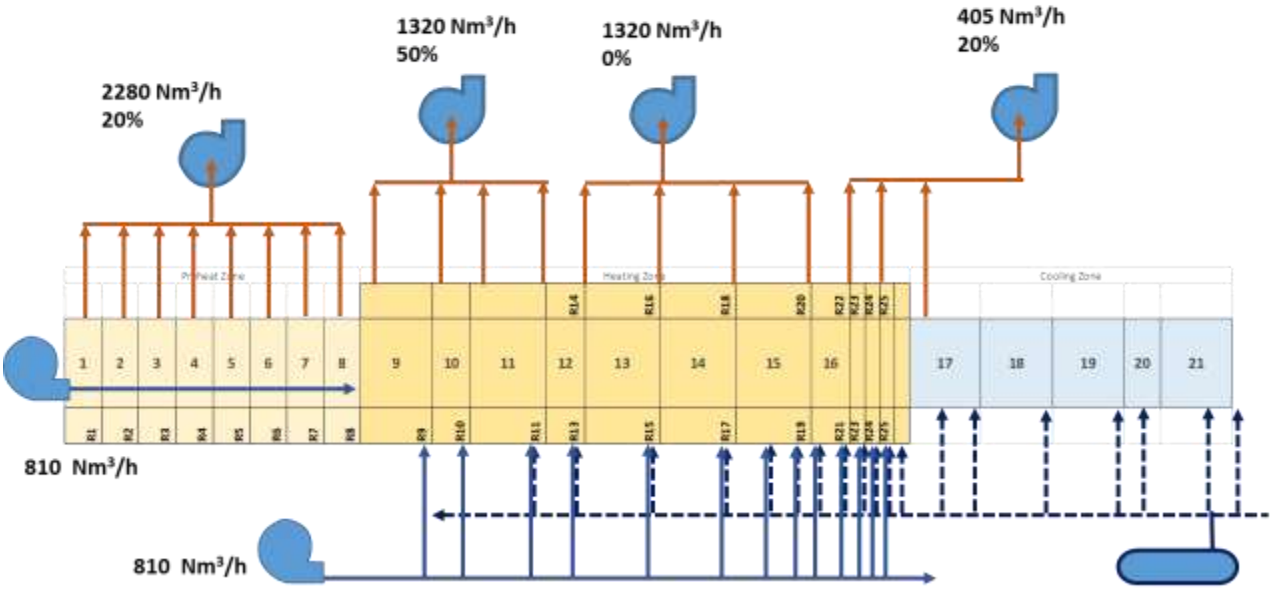

Fig.1 Schematic diagram of soft ferrite sintering furnace at Mahindra CIE, Bhosari

III. DEVELOPING MATHEMATICAL MODEL

To mathematical model all basic heat transfer path were formulated. Differential cross section of length dx were considered. All such differential cross sectional heat balance were integrated by putting local parameter like furnace core temperature, wall resistance and air inlet and outlet. Formula used are:

1. Heat carried by product and moving refractory

$$dQ_p = \dot{m}_p \times C_{P(product)} \times dT_x$$
$$dQ_r = \dot{m}_r \times C_{P(mov.ref)} \times dT_x$$

Where, $\dot{m}_p$ and $\dot{m}_r$ are mass of product and moving refractory going in furnace per second. $dT_x$is temperature difference along the length (*dx*) direction of furnace. $C_{P(product)}$ and $C_{P(mov.ref)}$ is specific heat of ferrite product and moving refractory respectively .

2. Heat loss by shell convection(Q_{conv})

$$dQ_{conv} = \frac{(T_{shell} - T_{amb})}{R_{conv}'} = \frac{(T_{shell} - T_{amb})}{R_{conv}} \cdot dx$$
$$R_{conv} = 1/(h * A)$$

Where, $R_{conv}'$is resistance per unit length (*dx*)A is shell area calculated as shell Perimeter (P) multiply by differential length *dx*.

3. Heat loss by shell radiation (Q_{rad})

$$dQ_{conv} = \sigma\epsilon(T_{shell}^4 - T_{amb}^4) \cdot P \cdot dx$$

Where $\sigma = 5.67 \times 10^{-8}\ \mathrm{W\,m^{-2}\,K^{-4}}$ Stefan–Boltzmann constant, $\epsilon = 0.3$ is emissivity of shell surface, P is perimeter of shell.

4. Heat loss through exhaust air

Each air exhaust location and air flows are listed down and energy lost through it is calculated and added to local energy consumption of furnace.

$$dQ_{air} = \rho_{air} \dot{V}_{air} C_{p,air} (T_{air,exhaust} - T_{amb})$$

Here ρ_{air} and $C_{p,air}$ are evaluated at air exhaust temperature $T_{air,exhaust}$. Volume flow rates of air ($\dot{V}_{air}$) are derived from blower capacities and percentage exhaust valve opening

Convective heat transfer coefficient at shell of furnace is due to natural convection and it is depends on shell temperature, while shell temperature is unknown and depend on heat convicted from shell. This inter-dependence make calculation of convective heat transfer iterative. An iterative algorithm was used to calculate convective resistance at each differential location along furnace length and used to calculate shell temperature of furnace. Wall thermal resistance is calculated using analytical approach with help of thermal conductivities and geometries of furnace. Wall consist of seven layer of insulation as given in Table 1

Table 1 Thermal conductivities of wall insulation material.

S. No	Material	W/mK
1	Alparit 75	0.302
2	JM23	0.174
3	JM26	0.337
4	JM28	0.385
5	OFL 54	0.280
6	Silli93	0.374
7	SL76LA	0.435

MATLAB script was written to carry out all calculation in developed mathematical model. Fig.2 shows flow chart of algorithm used to solve generated model.All input data as furnace core temperature, product and moving refractory mass flow rates and constant related to furnace construction is stored in a Furnace.xlsx file. In MATLAB script it is read and used for calculations. A sub routine using MATLAB script is used to calculate wall thermal and convective resistance of furnace and saved in database. According to formulae all heat energy paths are calculated and integrated. This result are shown using MATLABand also written to database for further analysis and representation.

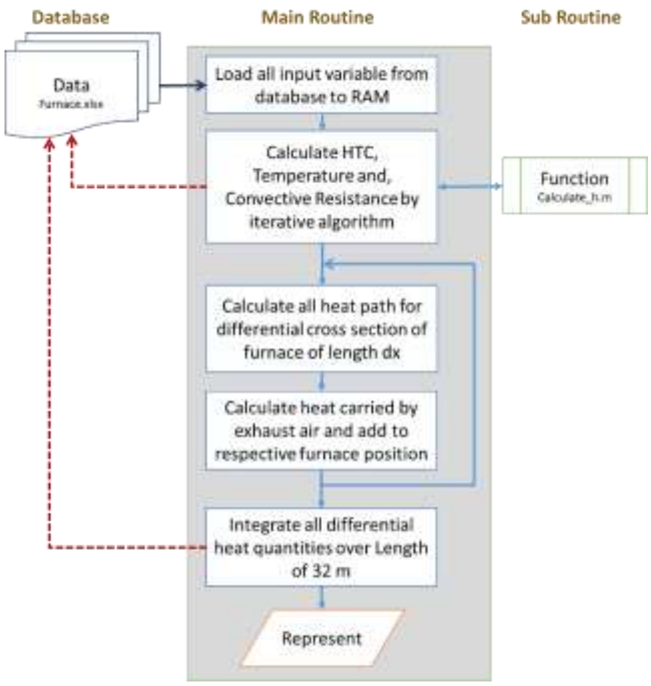

Fig.2 Flowchart of MATLAB algorithm developed to solve mathematical model.

Algorithm is checked for different differential length dx and found error of 0.13% between dx 0.5 m to 0.4 m in energy consumption per day variable. Algorithm takes average 33 sec to run on system of 2.4 GHz, 4GB RAM procedure.

3. Validation of simulation model

Validation of model is important phase in developing simulation model. The simulation model is validated using different measurements taken on soft ferrite pusher type sintering furnace (TP32) at Mahindra CIE, Bhosari.

2.1 Shell Temperature comparison

Shell Temperature of furnace was measured by non-contact type thermometer with emissivity set at 0.7. Temperatures are measured at conveniently accessible point between 8.5 m to 22.6 m along furnace which come under heating zone of furnace. Fig.3 shows actual and calculated shell temperatures.

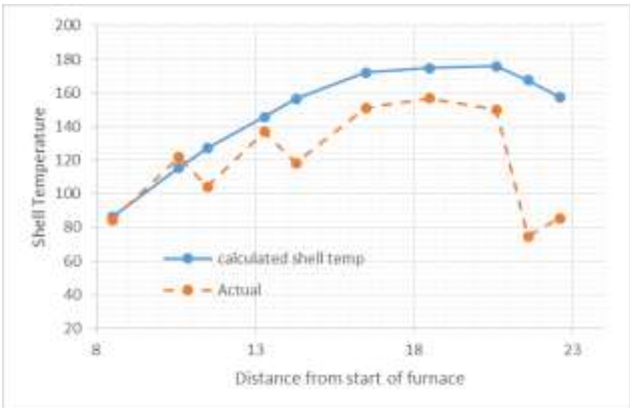

Fig.3 Actual shell temperature and Calculated shell temperature of furnace.

2.2 Comparison of predicted energy consumption with real energy consumption of furnace.

Energy consumption and tons of production of ferrite product are recorded every day by already available energy meters having. Such data for 7 months from 4-April-2015 to 4-Nov-2015 was taken to compare with simulation model energy consumption along with tons of product produced at these days. Specific energy consumption is calculated in both conditions and plotted along with real energy consumption in fig. 4. Dotted line in fig.4 shows regression fit to energy consumption and specific energy consumption with power law. Solid line are energy consumptions from simulated model and is generated by writing script in MATLAB. Plots in fig.4 shows good agreement with real physical behavior of furnace.

Residual plot of real energy consumption and simulated energy consumption in fig.5 shows randomized plot in region of 1.3 tons to 2.1 tons of daily production with offset of ~552 kWh. Offset of 552kWh on positive side almost constant for range of 1.3 tons to 2.1 tons of production might be due to lower assumed wall thermal resistance, as wall thermal resistance contribute to constant losses.

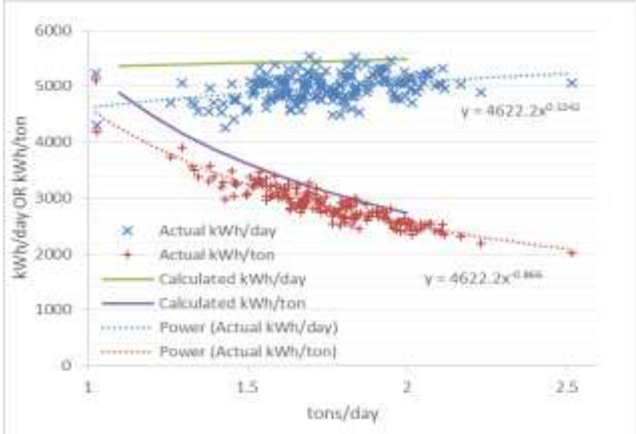

Fig.4 Energy consumption and specific energy consumption of furnace, comparison between real and simulated model data.

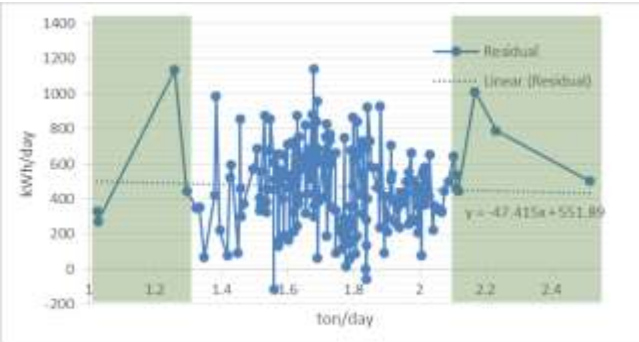

Fig.5 Residual plot between real energy consumption and simulated energy consumption.

IV. RESULT AND DISCUSSION

Fig.7 shows thermal energy going through various heat paths, asto product, moving refractory, shell convection and shell radiation in furnace. Green dot-dash line shows simulated energy needed by furnace at particular distance and solid blue line shows connected capacities of electric heater. Similarly other plots represent respective component of heat paths at each locations.

Total of 228.6 kW energy is provided by installed heater with capacity factor of 0.44. Only 4.3% of energy provided goes to ferrite product. 15.1% goes to moving refractories used to support product, which is higher than product due to more mass and greater specific heat of moving refractory. Moving refractory loss is varying lost depends on type and quantity of product. Shell conduction and shell radiation constitutes combined major and constant losses in furnace.

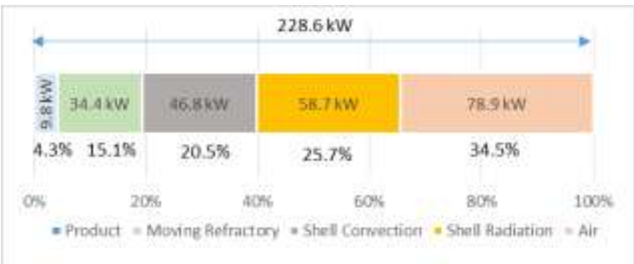

Fig.6 Overall energy constitutes of furnace.

Fig.6 shows overall energy constitutes of energy consumption where energy lost through exhaust air is maximum about 34.5% making air as concerned area of focus to improve performance. Modulating air flow will save energy requirement of furnace also exhaust air above 150^{o}C can be used to heat recovery.

Energy requirement is more at starting of heating zone from 9 m to 14 m due to higher change in temperature in length direction. In this zone heater are just able to give required heat. Heater in region of 16 m to 21 m are working at lower duty cycle and can be optimize for capacities. By calculation 35.8 kW of energy is lost in cooling zone to water cooling jacket and is verified using actual measurement of water temperatures and flow rate as 36kW. This amount of energy either can be used for drying of green ferrite product with suitable system.

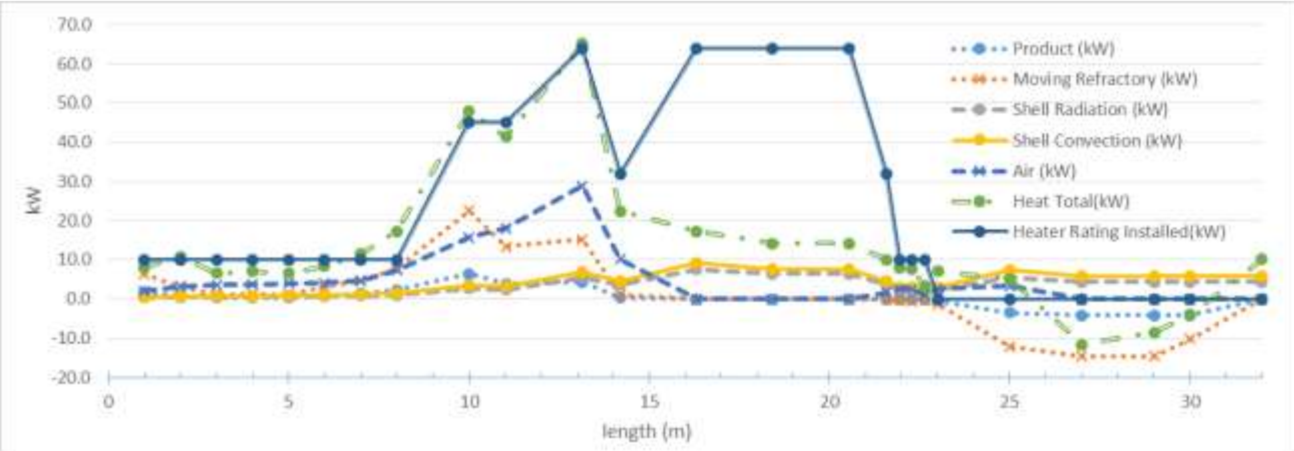

Fig.7localized constitutes of energy consumption of sintering furnace

V. CONCLUSIONS

Based on study done on long continuous furnace and one at Mahindra CIE, Bhosari following conclusions are derived

1) Long continuous furnaces are difficult to analyze due to complexities involve in mode of heat transfer and geometry. Even simplified CFD simulation of such furnaces renders it time consuming process. Hence mathematical model or semi-empirical mathematical model for such furnace gives more flexibility in analyzing, moreover it can be used to real time predictive control of furnace in changing furnace condition.
2) Mathematical model is developed for soft ferrite sintering furnace at Mahindra CIE, Bosari and simulated using MATLAB script. It showed that air is critical part in energy consumption followed by shell convection and shell radiation. Also heaters in heating zone have lower capacity factors and can be modified to increase capacity factor.
3) Energy conservation can be employed by recovering heat in exhaust air and used it to preheat air in preheating zone increasing furnace efficiency. Also heat lost from cooling section can be used to dry green ferrite product.

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