* Complete Manuscript including All Figs & Tables

Simulation of ceramic furnaces using one - dimensional model of heat transfer – Part II Optimization of fuel consumption

Sunil Gokhale [b], M. R. Ravi [a*], P. L. Dhar [a], and S. C. Kaushik [b]

Indian Institute of Technology, New Delhi, India

Abstract

The mathematical model for simulating heat transfer in ceramic furnaces has been developed and validated against experiment data obtained from different types of ceramic furnaces in part-I of this paper [1]. Based upon this methodology, a procedure for optimizing the firing cycle to minimize fuel consumption has been developed. Computer codes were written to optimize the gas flow rate through out the cycle to maintain a high level of combustion efficiency, while at the same time minimizing energy loss through flue gases. These programs were run for two kilns for three separate cases. In the first two cases a studio pottery kiln (kiln #1 in the companion paper) was studied for optimization with existing and with reduced thermal mass of kiln walls. In the third case optimization program was run for a laboratory scale kiln (kiln #2) that was built with reduced thermal mass of kiln walls. The data collected during a total of five firings have been used to corroborate the results of optimization. A comparison of the two sets of data of normal firing, with the three sets of data of optimized firing clearly shows that optimization strategy results in substantial savings of fuel. The utility of the optimization methodology is in predicting the optimal fuel flow schedule for a kiln, for a given firing cycle, thereby maximizing the thermal efficiency of the ceramic furnaces with minimal computational resources.

Keywords: Ceramic, Furnace, Kiln, Optimization, Heat transfer analysis, Firing, Simulation

[a] Department of Mechanical Engineering, [b] Center for Energy Studies,

* Corresponding Author, Tel.: +91 11 26591059; fax: +91 11 26582053

E-mail address: ravimr@mech.iitd.ac.in (M. R. Ravi).

Postal Address: Department of Mechanical Engineering, Indian Institute of Technology, Hauz Khas, New Delhi. Pin code – 110016, India

1.0 Introduction:

The development of a one-dimensional simulation model for gas fired pottery kilns and its validation against experimental data for different types of kilns was presented in a companion paper [1], referred to as "part I" in this paper. The present paper uses the one-dimensional model to optimize the fuel consumption of a pottery kiln. It has been observed in [1] that the flue gas losses contribute a major share of the energy loss in batch fired furnaces. The approach adopted in this paper attempts to minimize this component of loss to improve the energy efficiency of the kilns.

The amount of heat lost with the flue gases depends upon the amount of excess air supplied for combustion. To obtain complete combustion of fuel with the minimum amount of air, it is necessary to control air inflow rate by maintaining the draught. Higher excess air will reduce flame temperature, furnace temperature and heat transfer rate. At the same time, it reduces the residence time of hot gases in the furnace, thereby reducing the heat transfer efficiency, causing higher energy loss through flue gases. On the other hand, if the excess air is less, then combustion may not be complete, and this will also reduce the net heat transfer to the pots. The optimization of combustion air is thus essential, keeping both these aspects in view.

2.0 Optimization Methodology

For optimization we use the target firing cycle along with a fixed fuel-air ratio as inputs to the model. The air to fuel ratio of LPG-Air mixture was fixed at 10% excess air in all the optimization runs. The rate of fuel supply is calculated for every time step so that the chamber gas temperature follows a target firing schedule with this air-fuel ratio. The algorithm of optimization calculations is given in figure 1.

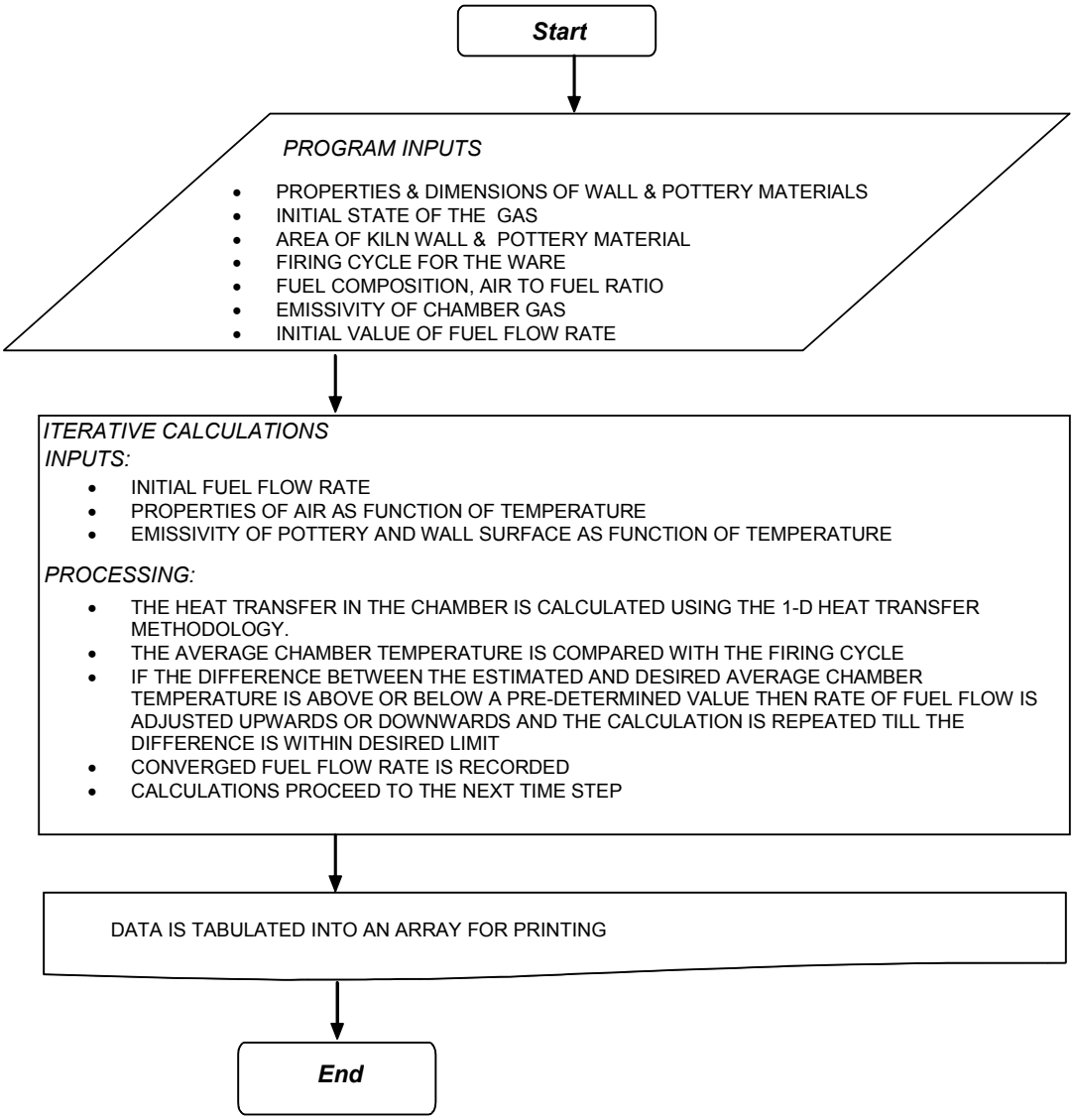

Figure 1: Flow Chart of Computer Program for Optimization

Heat transfer between the gas, pottery and wall is computed using the methodology described in details in part I [1] of this paper and description is omitted from here for brevity. The emissivity of wall and pottery-ware as a function of temperature has been accounted for in the computation.

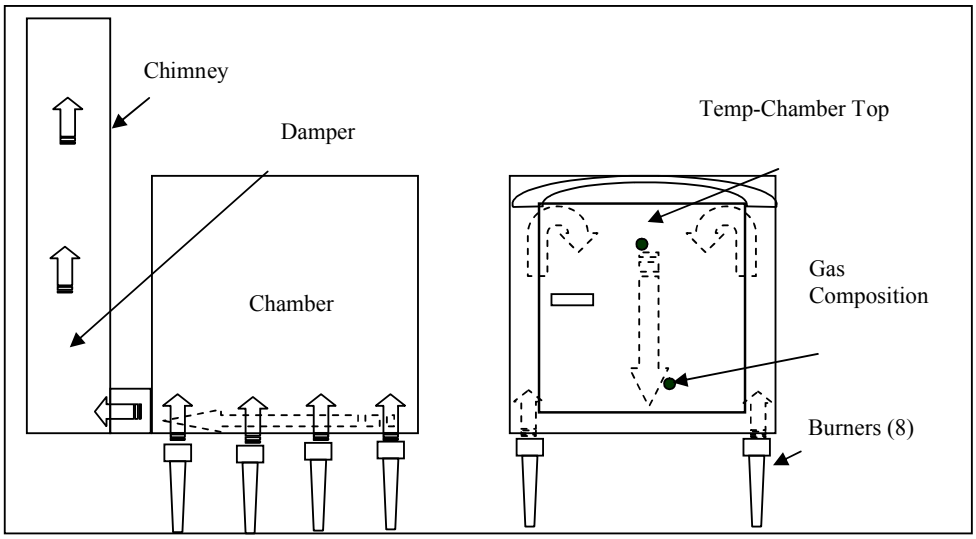

Figure 2: Schematic of a downdraft kiln#1

FORTRAN codes were written for each of the kilns to predict the optimized fuel supply from the target firing cycle. The program predicts the minimum fuel supply rate to achieve the desired firing cycle through an iterative procedure. After the run a comparison of normal and optimized fuel consumption is made to find the potential of fuel savings. The term "normal fuel consumption" is used to mean the amount of fuel used when the kiln is fired to maintain the firing cycle without any deliberate effort to control the air to fuel ratio, as is the normal practice followed by the artisans.

3.0 Optimization of Kiln#1

The kiln#1 is LPG fired, and of down draft type. The simulation methodology for this kiln was developed and validated in [1]. The schematic of the kiln is given in figure 2. Detailed specifications of the kiln are also given in [1]. This is a kiln of 1.728 m^3 internal volume. The wall is made of 2 layers, i.e. inner wall of 114.3mm thick

insulating brick, and outer wall of 114.3mm thick Ceramic Blanket. The target firing cycle followed is:

1. Ambient (23 ^{0}C) to 380 ^{0}C @ ~1 ^{0}C/min.
2. 380 ^{0}C to 1075 ^{0}C @1.5 to 2 ^{0}C/ min.
3. Soaking at 1075 ^{0}C for 60 min.

3.1 Kiln#1 optimization results:

The above firing cycle of Kiln#1 was used for estimate the optimized gas flow through the kiln#1 for the 2 cases as mentioned below. In both cases, thicknesses of the brick wall and insulation wall were retained the same, and only their positions were swapped. The optimization code follows the firing cycle within +/- 0.05 ^{O}C, while minimizing the gas flow through the kiln.

3.1.1 Kiln#1 optimization Case1 results:

Case 1: Computation of Optimized flow of gases was performed with existing wall construction i.e. insulating brick as inner wall and ceramic blanket as outer wall. The graph given in figure 3 indicates the comparison of fuel flow rates in case of normal firing (experimental) and optimized firing (computed). The pie-chart given in figure 4 indicates the optimized distribution of heat energy to various kiln components for Case 1.

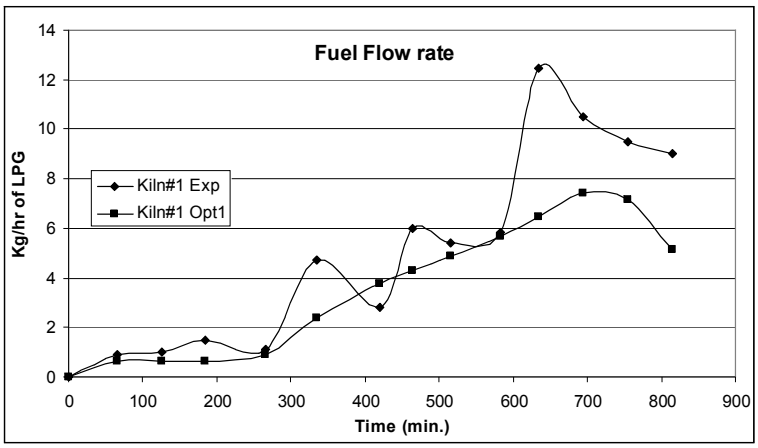

Figure 3: Fuel (LPG) Flow Rate in experiment (Kiln#1Exp) and computed optimal cycle- case 1 (Kiln#1 Opt1)

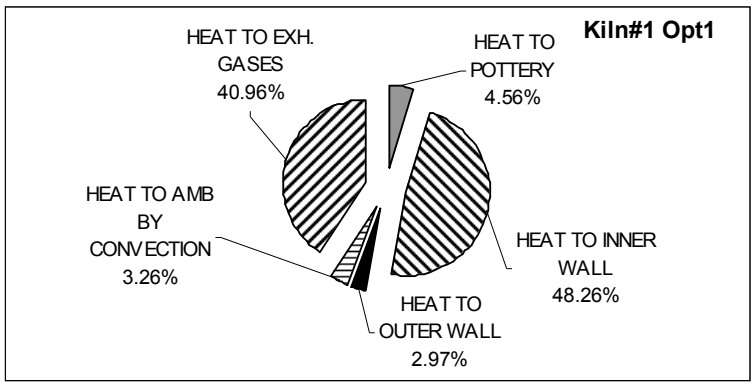

Figure 4: Optimized distribution of heat to kiln components in Kiln#1, Optimization Case 1

Table 1 indicates the comparison of energy distribution for Case 1A with that in Kiln#1 experiment covered in Part-I [1] in absolute and percentage terms. The optimization has effected the following changes from the experiment on kiln#1:

1. The efficiency has gone up from 3.42% to 4.56 %. The optimization strategy has drastically reduced the fuel consumption. The fuel consumption reduces from ~72 kg to ~49 kg.

2. Heat leaving with exhaust gases has reduced due to reduced flow of gases, from 1750 MJ to 864 MJ, in percentage terms 53.39% to 40.95%. This observation is in agreement with expectations.
3. In comparison with the experiment, the heat given to inner wall has increased from 38.26% to 48.25% in percentage terms, but in absolute terms it has reduced from 1254 MJ to 1018 MJ. For this case, the inner wall is made of high thermal mass insulating bricks that absorb more heat when the hot gases residence time increases.
4. The heat to outer wall and to ambient has reduced from 83 MJ to 63 MJ in absolute terms but in percentage terms it has marginally increased because the inner wall is getting hotter.

3.1.2 Kiln#1 optimization Case1A results:

Case 1A: Computations of Optimized flow of gases was carried out with a modified wall construction i.e. ceramic blanket modules as inner wall and insulating brick as outer wall. The pie-chart given in figure 5 indicates the optimized distribution of heat energy to various kiln components for Case 1A.

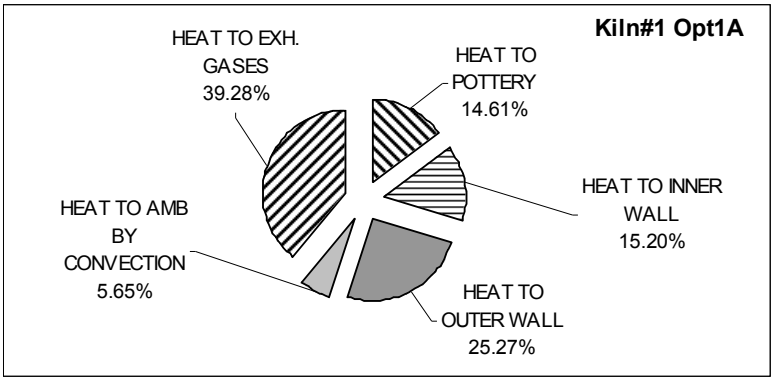

Figure 5: Optimized distribution of heat to kiln components in Kiln#1, Optimization Case 1A

Table 1 indicates the comparison of energy distribution in Kiln#1 experiment covered in Part-I, and optimized case1 of Kiln#1 firing cycle in absolute and percentage terms. The optimization case1A has effected the following changes from the experiment on kiln#1:

1. The efficiency has gone up from 3.42% to 14.61%, respectively. The optimization strategy combined with the reduction in the thermal mass of the hottest walls of the kiln has drastically reduced the fuel consumption. The fuel consumption reduces from ~72 kg to ~15 kg. Assessment of the effect of reduction in thermal mass of the inner wall can be made by comparing cases I and IA of kiln#1: The reduction in the fuel consumption is from 49 kg to 15 kg, accompanied by an increase in efficiency from 4.56% to 14.6%. However, in absolute terms, the energy absorbed by pottery is nearly the same in all three cases, viz., experimental, case I and case IA.
2. Heat leaving with exhaust gases has reduced due to reduced flow of gases, from 1750 MJ to 259 MJ, in percentage terms 53.39% to 39.28%. Comparing cases I and IA, the reduction due to reduction in thermal mass of inner wall is from 864 MJ to 259 MJ. This was expected.
3. In comparison with the experiment, the heat given to inner wall has reduced to from 1254 MJ to 100.05 MJ and in percentage terms from 38.26% to 15.2%, due to reduced thermal mass of inner wall, as well as reduced firing rates. Effect of reduced thermal mass alone, comparing cases I and IA, is a decrease in the energy absorbed by the inner wall from 1018 MJ to 100 MJ, a 90% decrease in absolute terms.

4. The heat to outer wall has much increased from 83 MJ to 166 MJ, and in percentage terms from 2.5% to ~27%, because now the outer wall is made of higher thermal mass.
5. The heat lost to ambient has also reduced in absolute terms from 79 MJ to 37 MJ, but has increased in percentage terms from 2.4% to ~5 %.

Table 1: Comparison of energy distribution to kiln#1 components between normal experimental firing and optimized case 1 and 1A.

S. no.	Kiln Component	Energy Distribution to Kiln Components					
		Kiln#1 Exp		Optimized Run Case1		Optimized Run Case1A	
		MJ	%	MJ	%	MJ	%
1	HEAT TO POTTERY	112	3.42	96	4.56	96.20	14.61
2	HEAT TO INNER WALL	1254	38.26	1018	48.25	100.05	15.20
3	HEAT TO OUTER WALL	83	2.53	63	2.97	166.37	25.27
4	HEAT TO AMB BY CONVECTION	79	2.41	69	3.26	37.17	5.65
5	HEAT TO EXH. GASES	1750	53.39	864	40.95	258.63	39.28
6	EFFICIENCY		**3.42**		**4.56**		**14.61**
7	**FUEL CONSUMED IN (KG)**	**71.71**		**48.73**		**15.20**	

3.2 Inferences from kiln#1 optimization:

From the kiln#1 optimization run, we can infer that:

1. By reducing the gas flow we can reduce flue gas flow, and reduce the specific fuel consumption of the kiln.
2. By reducing both gas flow as well as the thermal mass, we achieve a very substantial improvement in efficiency, accompanied by a significant reduction in fuel consumption.
3. By optimizing the experiment data of kiln#1 to case 1 and case 1A, the gas consumption reduces from 72 kg to ~49 kg and then to ~15 kg, respectively and the heat lost with the exhaust gases reduces from 1750 MJ to 864 MJ and then to 259 MJ, respectively.

4.0 Optimization of Kiln#2

Kiln#1 is a privately owned studio pottery kiln and therefore it was not possible to modify it or use it for optimization experiments. Therefore, as mentioned in Part-I [1], a laboratory scale kiln#2 was built with a low thermal mass to validate the model as well as to study the effect of reduced thermal mass of the inner wall. The schematic of kiln #2 is given in figure 6.

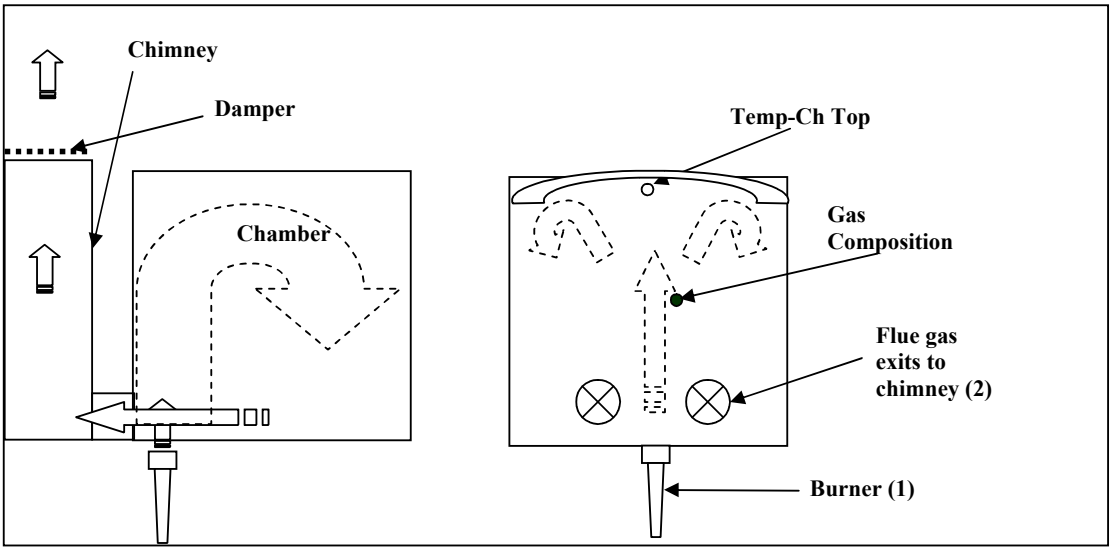

Figure 6: Schematic of a downdraft kiln#2

This is an LPG fired kiln of 0.0788 m^3 inside volume. The wall is made of 2 layers, i.e. inner wall of 228.6mm thick ceramic fibre module, and outer wall of 114.3mm thick red brick. Details of this kiln are described in appendix II of part I [1].

Target Firing cycle:

1. Ambient (27 ^{0}C) to 150 ^{0}C @ 1 ^{0}C/min.
2. 150 ^{0}C to 450 ^{0}C @ 2 ^{0}C/min.
3. 450 ^{0}C to 720 ^{0}C @ 3 to 4 ^{0}C/min.

4.1 Kiln#2 optimization results:

The above firing cycle of Kiln#2 was used for optimization of gas flow through the kiln#2.

The optimization codes follow the firing cycle within +/- 0.05 ^{O}C, while minimizing the gas flow through the kiln. The pie-chart given in figure 7 indicates the optimized distribution of heat energy to various kiln#2 components:

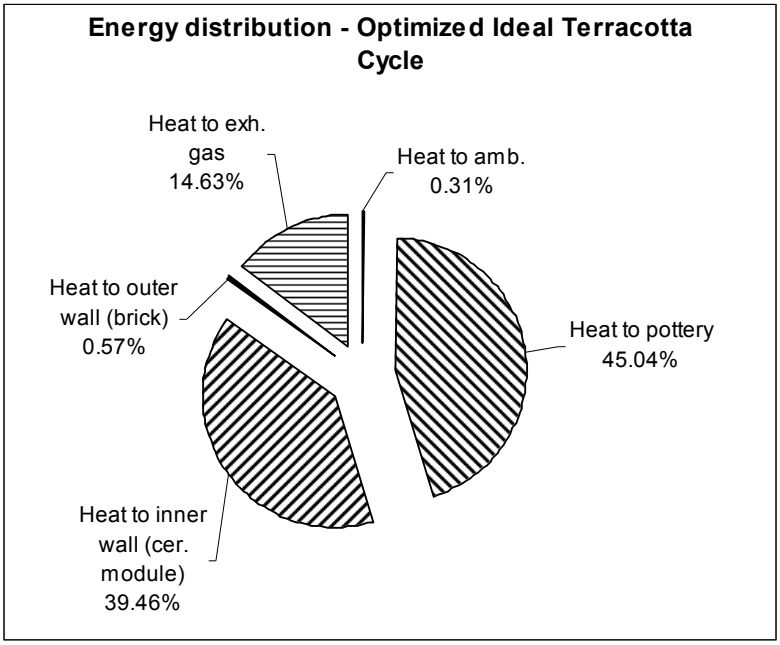

Figure 7: Optimized distribution of heat to kiln components in Kiln#2, Computed

Table 2 indicates the comparison of energy distribution in Kiln#2, experiment#1 presented in the Part-I paper [1] and the optimized run of Kiln#2 firing cycle presented above.

The optimization run has effected the following changes:

1. The fuel consumption reduces from ~5 kg to ~0.7 kg. The efficiency has gone up from 15.7% to 44.87 %. The optimization strategy has drastically reduced the specific fuel consumption.
2. Absolute amount of heat lost with exhaust gases has reduced due to reduced flow of gases from 70.2 MJ to 4.73 MJ, and in percentage terms from 70% to about 15%. This has a major impact on the overall efficiency.

Table 2: Comparison of energy distribution to kiln#2 components, between normal experimental firing and optimized case

S. no.	Kiln Component		Energy Distribution to Kiln Components			
			Kiln#2 Exp#1		Optimized Kiln#2	
			MJ	%	MJ	%
1	HEAT TO POTTERY		15.54	15.75	14.55	45.03
2	HEAT TO INNER WALL		12.96	13.13	12.75	39.46
3	HEAT TO OUTER WALL		0.18	0.18	0.18	0.56
4	HEAT TO AMB BY CONVECTION		0.10	0.10	0.11	0.32
5	HEAT TO EXH. GASES		70.20	71.13	4.73	14.62
6	EFFICIENCY			**15.75**		**45.03**
7	**FUEL CONSUMED IN (KG)**		**5.02**		**0.71**	

3. The heat given to inner wall has increased from 13% to 40% in percentage terms but in absolute terms it is not changed and is at ~13 MJ, due to lower gas flow and increased residence time of the gases.
4. The percentage heat to outer wall and to ambient does not change in absolute terms but in percentage terms has increased (although marginally) because the inner wall is getting hotter.

4.2 Experimental verification of kiln#2 optimization results:

Kiln#2 is a laboratory scale kiln at IIT Delhi, on which experiments were conducted for validation of simulation model and later for verification of optimized predictions. Optimization experimental data was collected and compared with the data of normal running (Kiln#2, experiment #1 given in Part-I). The reduction in excess air and optimization strategy was applied to the standard firing cycle given above that was optimized. Table 3 gives the comparison of normal running, optimized prediction and optimized experiment in terms of firing schedule, time taken, excess air used and fuel consumed. It is observed that excess air control in the first two stages of firing is not as effective as desired. This was due to the inadequacy of the damper arrangement of the kiln. However, during the third stage (rapid firing), the excess air could be closely controlled as per requirement given by the optimization calculations. Thus, comparisons are discussed for the rapid firing phase alone for optimization experiments on this kiln.

Table 3: Comparison of average excess air supply and the total fuel consumption between Kiln#1, normal experimental firing #1, Ideal Optimized Cycle Prediction, and Optimized Experiment

Case	Temperature Rise	Total Time	Average Excess Air	Total Fuel
	^{0} C	Minutes	%	Kg of LPG
Kiln#2, Exp#1	50 to 753	360	707	5.03
Ideal Optimized Cycle	27 to 807	360	10	0.63
Optimization Experiment	14 to 751	400	246	2.49

The chamber temperatures (firing schedule), excess air percentages, rate of fuel consumption, and cumulative fuel consumption through out the firing cycle have been plotted on figures 8, 9, 10 and 11.

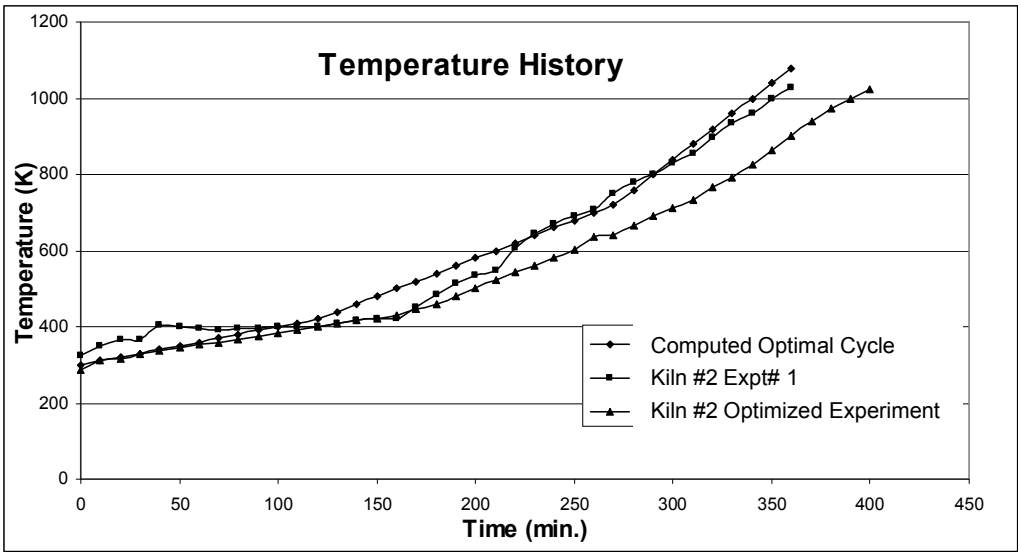

Figure 8: Temperature history of Kiln#2, Exp#1, Computed Optimal Cycle, and Kiln#2 Optimized Experiment.

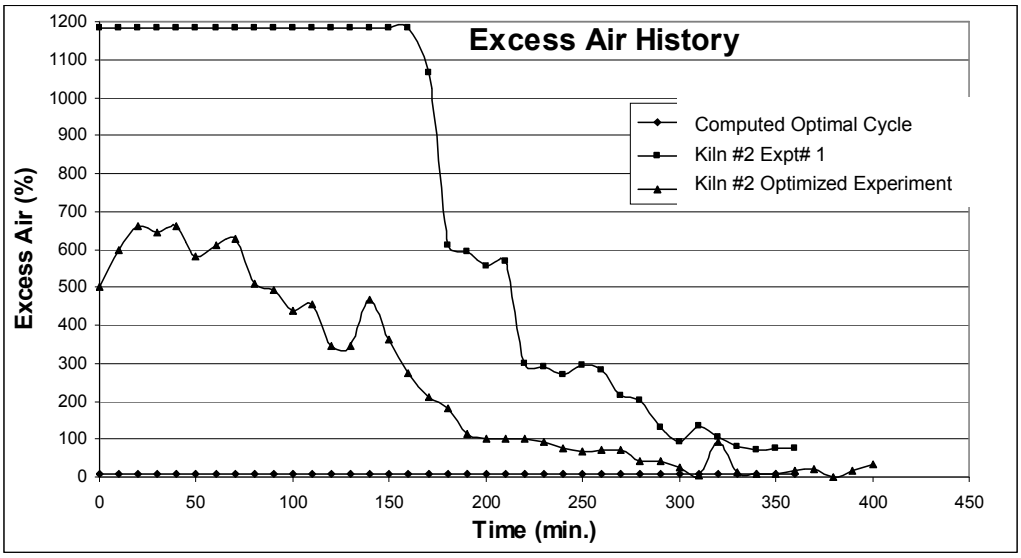

Figure 9: Excess air variations of Kiln#2, Exp#1, Computed Optimal Cycle, and Kiln#2 Optimized Experiment

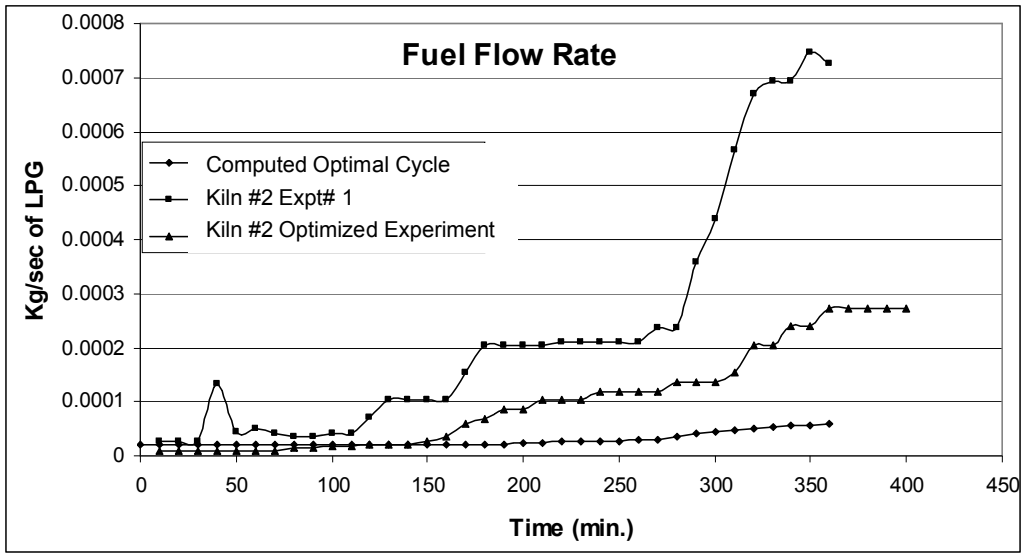

Figure 10: Fuel (LPG) Flow Rate of Kiln#2, Exp#1, Computed Optimal Cycle, and Kiln#2 Optimized Experiment.

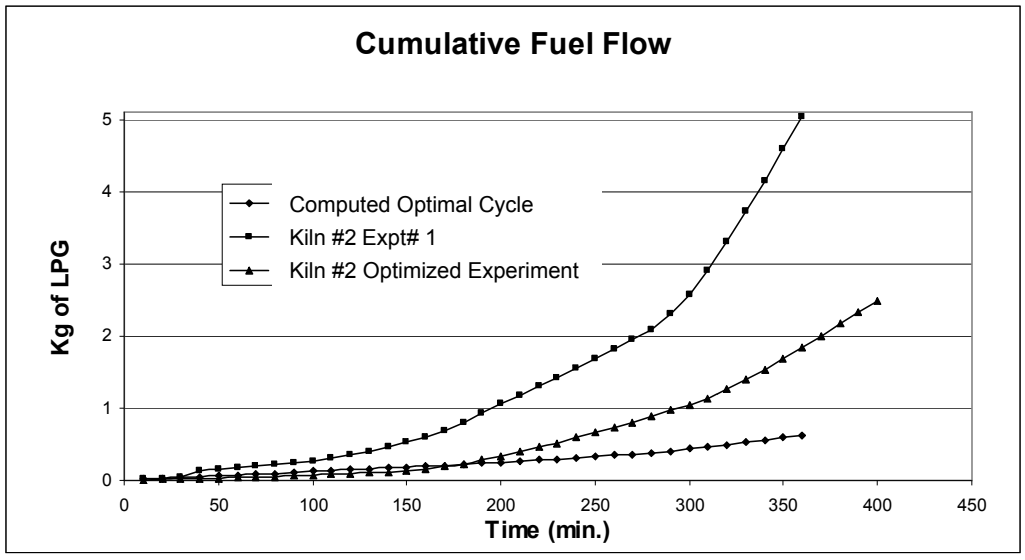

Figure 11: Cumulative LPG consumption of Kiln#2, Exp#1, Computed Optimal Cycle, and Kiln#2 Optimized Experiment.

4.4 Inferences from kiln#2 optimization experiments:

The optimization experiments have had the following effects on the performance of kiln#2:

1. As the average excess air supplied during the fast firing stage reduces from over 200% to below 30%, the fuel consumed by the furnace reduces from ~2.5 kg to ~1.5 kg in the fast firing stage. Therefore, the optimization strategy has led to a drastic reduction in the specific fuel consumption.
2. This is a reduction of about 30 to 35% in fuel consumption during the rapid firing phase.
3. The predictions of optimized run are agreeing fairly in trend with the measurements, and hence can be used with confidence for modification of firing schedule to optimize the thermal efficiency of the kilns.

5.0 Conclusions:

1. The 1-D optimization is successful in predicting the firing schedule of a batch type ceramic kiln. The predictions are agreeing fairly in trend and values with the measurements, and hence can be used with confidence for optimization of firing schedules to improve the thermal efficiency of the system.
2. The model is much simpler in estimating the fuel supply rates to achieve a target firing cycle than a 2 or 3 dimensional Computational Fluid Dynamic Analysis. The program does not need a high end PC.
3. The heat distribution pattern of Kiln#1 and Kiln#2 indicated that we need to reduce heat flow to the wall, by reducing thermal mass of the kiln, and to

reduce the heat flowing out with flue gases, by reducing the gas flow through the kiln.

4. The energy distribution results in kiln#1 experiment were used successfully to design and build a laboratory scale kiln#2 of low thermal mass. The five experiments performed on Kiln#2 have again validated the simulation (Part-I) as well as the optimization models. The heat distribution shows reduced heat flows to inner wall and improved the thermal efficiency.
5. An optimization strategy has been developed using the simulation model to improve the combustion efficiency of the kiln. These codes were run on the kiln#1and kiln#2 configurations. The results indicate that the reduction in gas flow, by supplying minimum amount of excess air is quite promising. Scope for improvement in thermal efficiency from 3% to 14% has been predicted for kiln#1. In case of kiln#2, scope for improvement in thermal efficiency from 14% to 44% has been predicted and verified experimentally.

6.0 References:

[1] Sunil Gokhale, M. R. Ravi, P. L. Dhar, and S. C. Kaushik, Simulation of ceramic furnaces using one-dimensional model of heat transfer – Part I: Model development and validation, Indian Institute of Technology, New Delhi, India, Sept 2007.