A Study Towards Energy Saving in Brick Making Part 3 : Experiment Verification and Operation Strategy

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ABSTRACT

In a series of studies aiming for the development of an energy-efficient brick kiln, experiment verification of the theoretical simulation reported previously is presented. Three experiments were carried out in a full-scale single chamber kiln loaded with 3500, 2500 and 2250 bricks. It was found that the experimental results agreed well with the theoretical prediction particularly at the small loading capacity. Since the proposed four-chamber kiln requires time matching of the four processes, the operating times and associated temperatures in the four chambers were studied by the computer simulation. It was found that the production cycle consists of two subcycles of which the durations are alternately long and short and the specific energy consumption are low and high. The specific energy consumption depends on the firing temperature, combustion air flow rate and loading capacity. The kiln with a low loading capacity does not only consume less specific energy but also completes the process in a shorter time ; hence increases the production rate at low unit cost. In general, the specific energy consumption, under the conditions of this study, is in the range of 1.4 MJ/kg - 2.4 MJ/kg brick.

1. INTRODUCTION

Brick making in developing countries still consumes energy inefficiently, though there is scarcity in fuel available. There is therefore an urgent need to acquire knowledge and understandings that lead to the development of an energy-efficient brick kiln. In Part 1 of this study, the key parameters responsible for the energy saving and a basic concept of an energy-efficient kiln were given [1]. It was established that the firing time, temperature, brick setting pattern and waste heat recovery are the key factors for the energy saving and should receive further investigations. The manipulation of the firing time and temperature and waste heat utilization to minimize the energy consumption was studied theoretically by computer simulation and was presented in Part 2 of this study [2]. A concept for a four-chamber kiln working together in the four processes namely, cooling, firing, preheating and drying, was proposed. However, a study aiming to develop an energy-efficient brick kiln cannot be completed unless the simulation results are verified by actual experiments. In addition, as the four processes involve heat and mass transfer at different levels of temperatures, it is, likely that different processes may take different times to finish. Thus, operating time matching of the four processes is another important factor that has to be taken care of.

This paper reports the results of experiments carried out in a full-scale kiln in order to verify the simulation results and gain confidence before proceeding to the final step, the full-scale four-chamber operation. An operating time matching strategy for the four processes was also studied and is presented.

2. EXPERIMENTAL VERIFICATION

2.1 The Kiln and Experimentation

A down-draft kiln was constructed for the experimental verification. The walls were constructed from bricks and mortar while the roof was made from fire-resistant cement. The door was a steel sheet insulated by caowool ceramic fiber of 50 cm thickness. The internal dimension was measured as 1.6 x 2.2 x 1.7 m^3 which can accommodate up to 3500 bricks. A furnace and a fire barrier (to force the hot gas upward and then downward on the brick pile) were on one side. The fire barrier had 5 x 5 cm^2 holes that allowed cross draft for the bricks set adjacent to the wall. The exhaust channel was on the opposite side down on the floor where a blower was used to create draft as shown in Fig. 1. The combustion product flow rate, which was adjustable, was measured by a calibrated orifice. The firewood fed into the furnace was weighed and the subsequent consumption rate was computed. Every piece of firewood was cut in the middle for a slice of approximately 1 cm thick which was used for the moisture content evaluation. Temperatures on the wall surfaces and of the exhausted gas were recorded for the calculation of heat loss. Temperatures of the hot gas on the top of the brick pile (firing temperature) and within the brick pile at three levels (Fig. 1), nine locations in each level, were continuously monitored. All temperatures were measured by type k thermocouples and recorded by a multichannel data logger. Green bricks of known average moisture content were set inside the kiln. Therefore, in a batch of an experiment the processes of drying, preheating, firing and cooling occurred in sequence. The accuracy of the simulation program developed in Part 2 [2] was evaluated from the

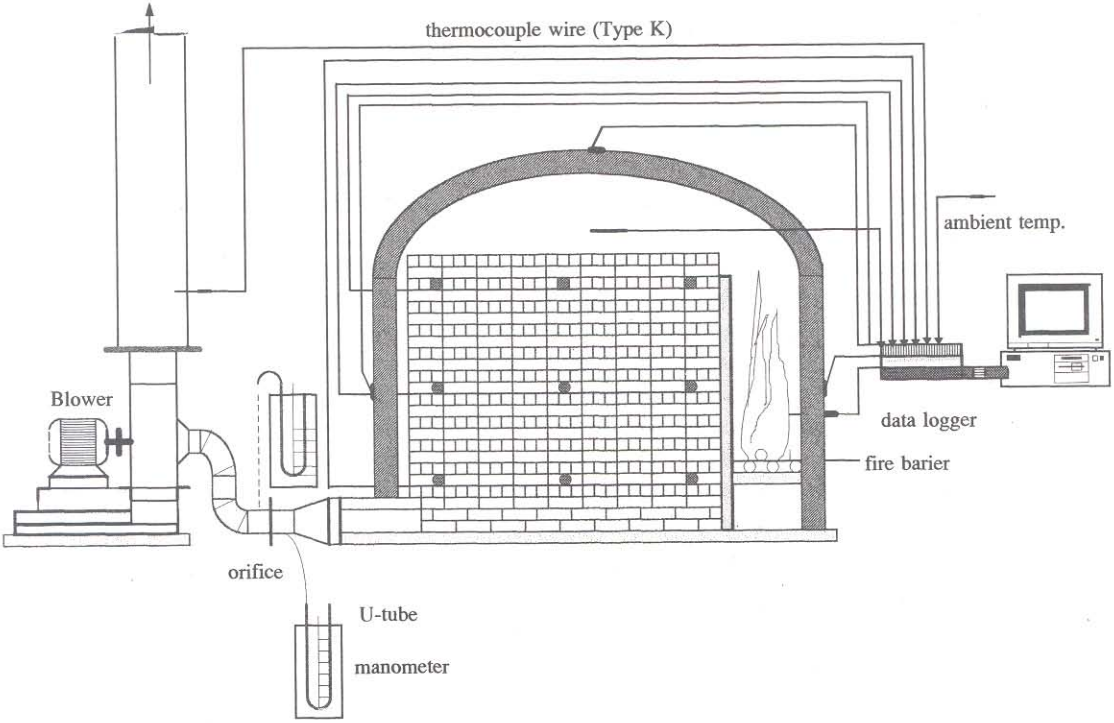

Fig. 1 Experimental kiln set-up.

2.2 Temperature Distribution and Energy Consumption

Three experiments were conducted, with the numbers of bricks loaded in the kiln being 3500 bricks (Test 1), 2500 bricks (Test 2) and 2250 bricks (Test 3). The void ratio of the brick setting in every test was 0.357. The void ratio was determined from the volume of air gap divided by the bulk volume of the brick pile. The average moisture contents of the green bricks for Tests 1, 2 and 3 were 9.4%, 12.1% and 13.2% (dry basis), respectively. The corresponding values for the firewood moisture contents were 21.9%, 35.0% and 34.7%.

Figs. 2 - 4 give the temperature distribution in the brick piles of Tests 1-3. There is evidence in Fig. 2 that the bricks in the bottom and middle layers were at low temperature compared to the top layer at the highest loading capacity, due to the high thermal inertia, during the water smoking period (bottommost brick temperature was less than 110 °C). The end of the water smoking was indicated by the absence of white smoke at the chimney outlet. The water smoking period of Test 1 took about 20 h which was much longer than those of Tests 2 and 3, even though the initial brick moisture (of Test 1) was lower. After finishing the water smoking, the firing temperature of all tests increased at the same rate, i.e., 600 °C within about 20 hours.

The firing process was completed when the temperature of the bottom-layer bricks reached 600 °C. Temperatures of the three layers plotted in Figs. 2 - 4 represent the average values of 9 measurements in a layer. The average temperature of the bottom layer was less than 600 °C which implied that some bricks in the bottom layer were still underfired, i.e., were exposed to the temperature of less than 600 °C. The thermal shadow areas were the four corners and along the fire barrier. The percentage of the underfired bricks in Tests 1, 2 and 3 were 15%, 10% and 5%, respectively. The firing times of Tests 1, 2 and 3 were 50 h, 36 h and 31 h, respectively. The firing retention time (at 800 °C) of Test 1 was about 13 h which was relatively long compared to those of 5 h and 2 h of Tests 2 and

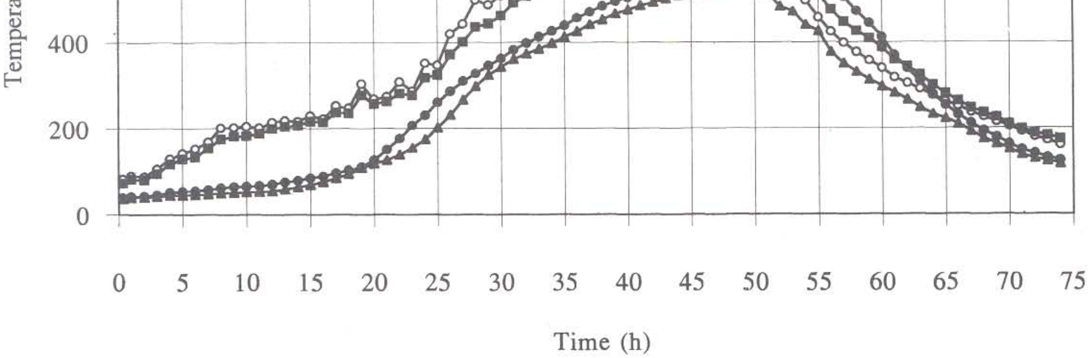

Fig. 2. Temperature profiles in the brick pile (Test 1).

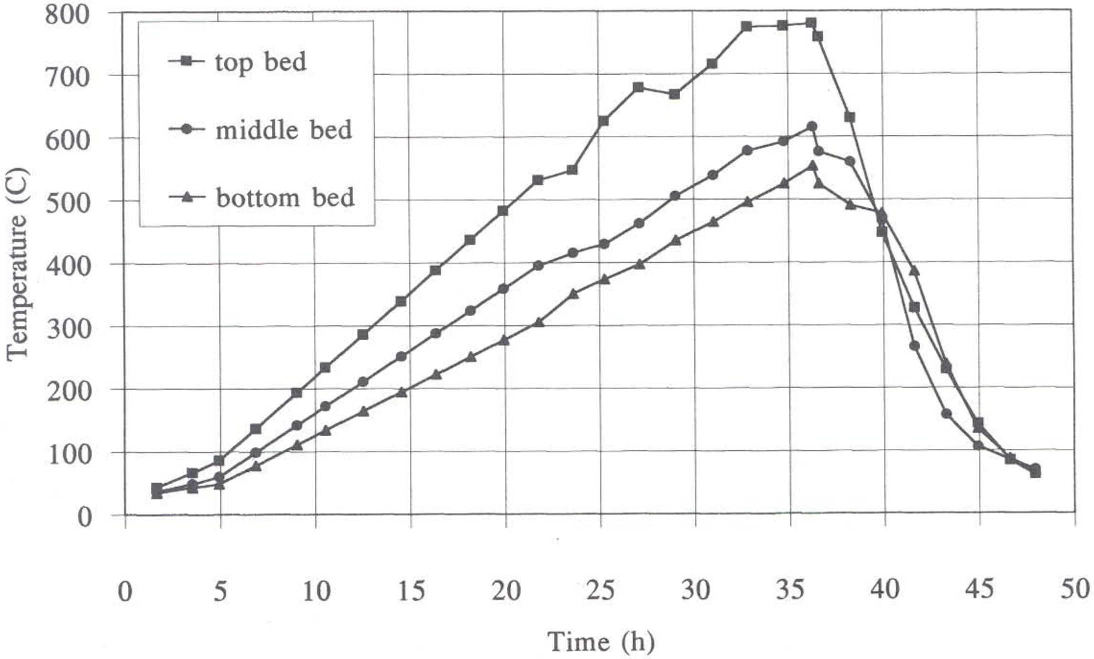

Fig. 3. Temperature profiles in the brick pile (Test 2).

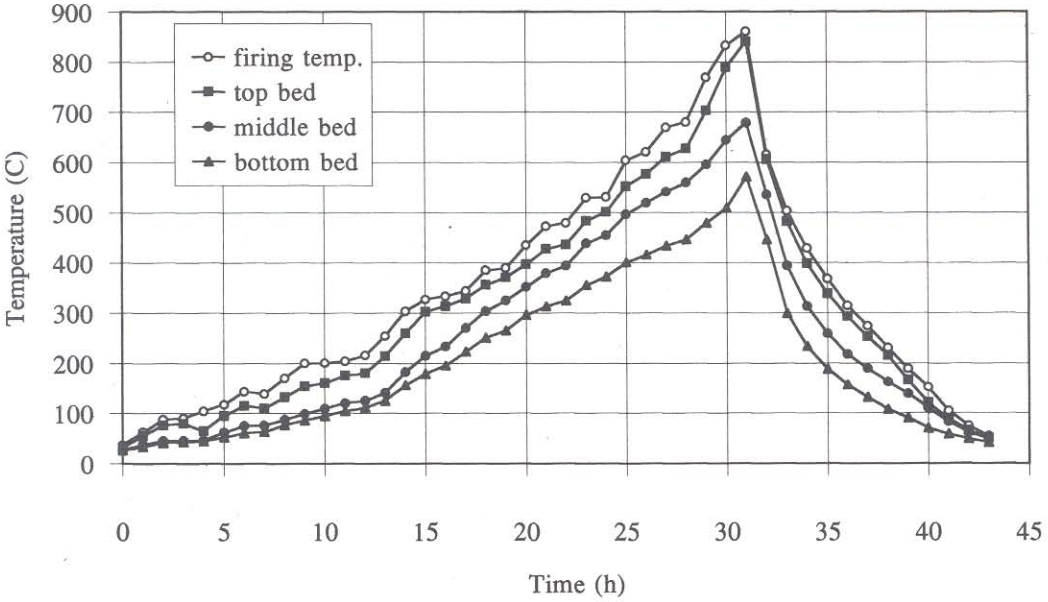

Fig. 4. Temperature profiles in the brick pile (Test 3).

3, respectively. The longer retention time of Test 1 was a result of a higher thermal inertia of the 3500 brick pile. Consequently, the cooling time, which was the time required to bring the brick temperature down to 100 °C, of Test 1 was over 25 h while the corresponding figures for both Tests 2 and 3 were 10 h only. The size of the brick pile (or kiln) affects the firing time and, consequently, the energy consumption as was found in the previous study [2].

The energy consumption of each process can be determined from the firewood consumption in that process. The drying, preheating, firing and cooling processes finished when the bottom layer bricks reached the temperatures of 110 °C, 400 °C, 600 °C and 100°C, respectively. It was found from the three tests that the energy consumptions in the drying, preheating and firing processes were 10%-26%, 19%-30% and 50%-62% of the total, respectively. Energy flow during the processes was classified and shown in Table 1. The heat losses were calculated based on the measured temperatures, masses and mass flow rates.

The specific energy consumption was in the range of 4.0 MJ/kg - 4.3 MJ/kg. This figure is relatively high compared to those obtained from the simulation results [2] or derived from the laboratory-scale experiment [1] because the bricks were not preheated and the still very hot gas was released to the surroundings. In addition, the combustion air was not preheated by the bricks in the cooling chamber as was simulated. The very low specific energy figure of 0.966 MJ/kg reported in [1] was the clay-to-brick transformation energy, not the energy required for the brick making. As a matter of fact, this experiment was actually a batch production similar to the traditional kilns, which also consume about 4 MJ/kg - 5 MJ/kg [3].

2.3 Verification of the Simulation

The construction of a full-scale four-chamber kiln for further experimentation is not only costly but the success is also doubtful particularly in the complementary manner of operation where the air is preheated and the waste heat is recovered. In order to assure the success, the results obtained from the single kiln experiment were used to verify the simulation program and procedures developed previously [2]. The experimental and simulation results of the bottom layer temperature and the wood consumption rate are given in Figs. 5-7. In the simulation, the brick pile was considered as comprising

Table 1. Energy flow in the brick firing tests.

	Test		
	1	2	3
No. of bricks	3500	2500	2250
Total energy consumption (MJ) *	17047	12861	11327
Specific energy consumption (MJ/kg)	4.06	4.29	4.20
Energy flow			
- conduction loss (MJ, %)	676.3, 4%	580.5, 4.5%	282.2, 3%
- stack loss (MJ, %)	7231.5, 42%	6465.3, 50%	6001.7, 52%
- storage in kiln structure (MJ, %)	3076.5, 18%	2554.4, 20%	2709.1, 24%
- storage in bricks (MJ, %)	6063.5, 36%	3260.0, 25%	2332.2, 21%

* Determined from firewood heating value of 16 MJ/kg

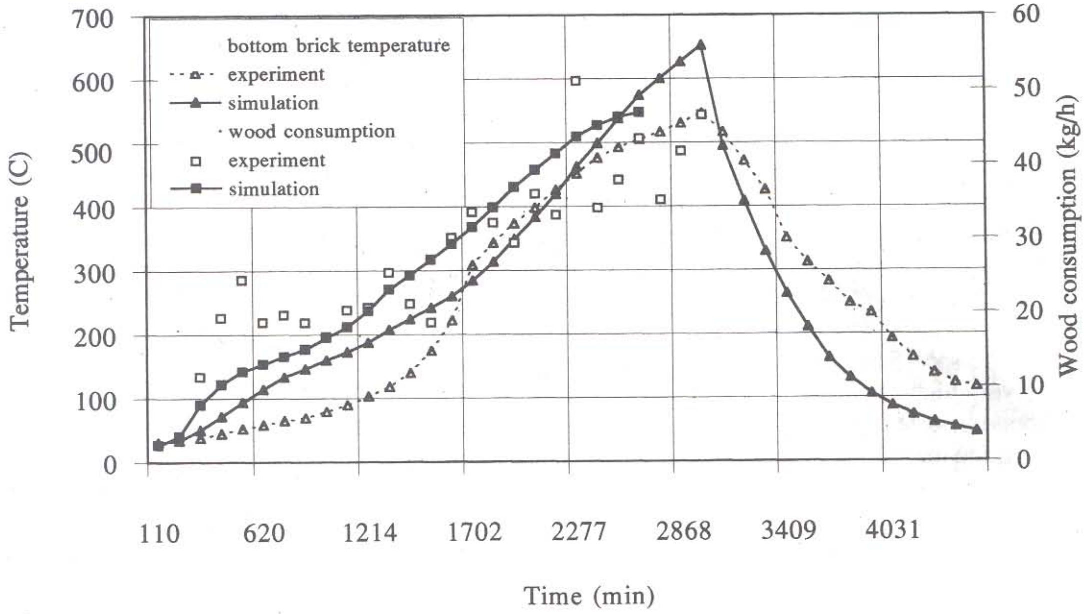

Fig. 5. Simulation and experimental results of bottom bed brick temperature and wood consumption rate (Test 1).

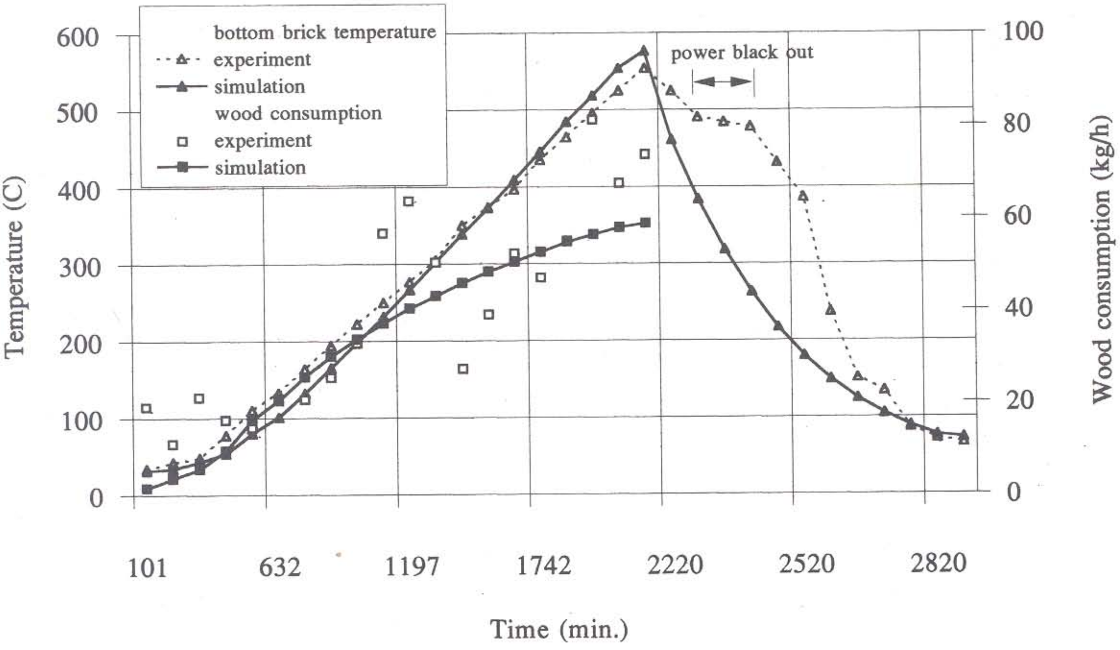

Fig. 6. Simulation and experimental results of bottom bed brick temperature and wood consumption rate (Test 2).

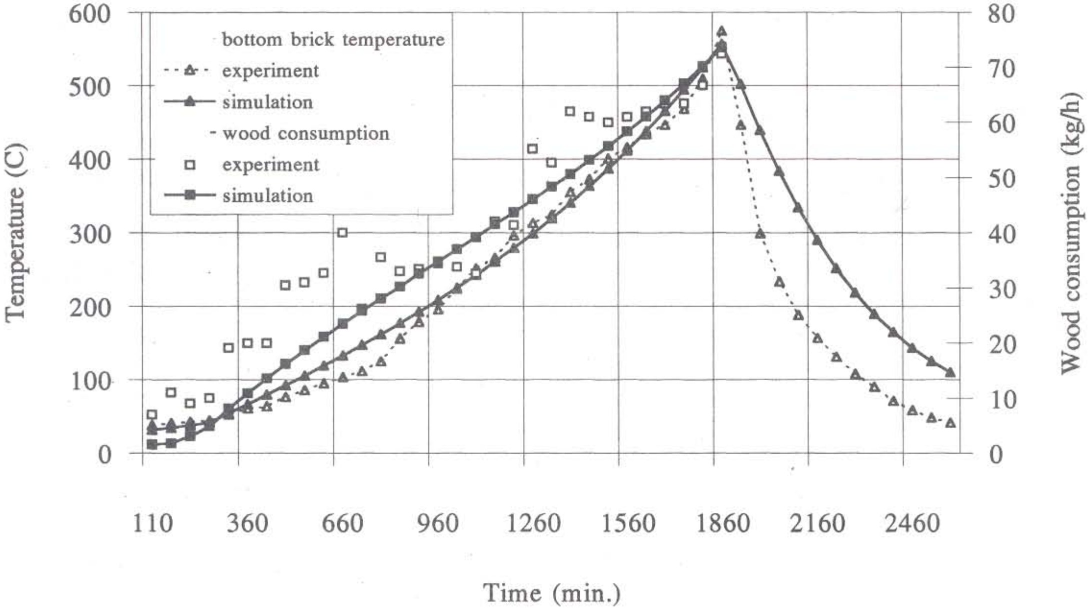

Fig. 7. Simulation and experimental results of bottom bed brick temperature and wood consumption rate (Test 3).

of several layers and the fixed bed model was used [2]. The brick temperature in the kiln was calculated from the top bed downward to the bottom bed. The bottom layer temperature was used for the verification because the error, if any, is likely to accumulate at this last layer (bed) of the calculation.

Taking into account the possible cummulative error, the simulation can predict the temperature quite accurately especially if the loading is 2500 bricks or less. However, an error in the range of 100 °C was experienced during the cooling process. The abnormality of the cooling curve in Fig. 6 was a result of power black out during the experiment which disabled the blower to cool the bricks. It is likely that the simulation predicts higher temperature after the end of the cooling process. It is believed that the cold air, because of less buoyancy force, provided cross draft through the holes along the fire barrier wall and cooled the bottom layer bricks. The very high loading density in Test 1 (Fig. 5) allowed less cross draft during the cooling; thus yielded different cooling profile. The wood consumption rates measured from the experiments were very scattered due to the discrete nature of data, i.e., the firewood was fed in a batch. Furthermore, the simulation results were based on the average moisture content of the wood and a fixed ambient condition (30 °C, 80% RH) while the actual wood feeding rate at a particular moment depended on the temperature in the kiln and the moisture of both wood and air at that moment. Moisture in the wood is an influential factor that significantly reduces the flame temperature and the increase of wood burning rate is needed in order to achieve the required firing temperature. The scattered data are, therefore, considered acceptable in this kind of engineering experimentation.

3. TIME MATCHING OF THE PROCESSES

3.1 Simulation of Operation Cycle

It becomes obvious from Figs 2-4 that the times required for the drying, preheating, firing and cooling processes are not equal. Unless the time mismatching problem of the four processes is solved, the principle of the cooperative four-chamber kiln is not applicable. A study toward the time matching solution was carried out by using the simulation equations developed in Part 2 [2] which have been proved in the aforesection. The simulation results are presented for the combustion air flow rates of 800 kg/h, 900 kg/h, 1000 kg/h, 1100 kg/h and 1200 kg/h, the kiln capacities of 2200, 2600 and 3500 bricks and the firing temperatures of 800 °C, 900°C and 1000 °C. The brick dimension is $6 \times 8 \times 19$ cm^3 and the unit mass is 1.2 kg. The brick setting gives the void ratio of 0.348 and the surface to volume ratio of the brick pile of 5.6 m^{-1}. The firewood heating value is 16 000 kJ/kg, with a 20% moisture and 4% ash content.

The four processes in the four-chamber kiln are illustrated in Fig 8. Only a brief simulation process is discussed here. Full detailed simulation was given in Part 2 [2]. The simulation started by assuming the top layer bricks in the cooling chamber were at the firing temperature. Previous study [2] found that the temperature decreased linearly with the depth of the brick pile and the temperature at the bottom layer was assumed at 650 °C. The cooling air, which later becomes the combustion air, is heated up. However, its temperature decreases with time as the bricks are cooled down. The decreasing temperature of the combustion air was taken into account of the firewood burning rate computation in order to maintain a constant firing temperature. Similar heat transfer simulation was applied in the firing and preheating chambers. The initial temperatures in the firing, preheating and drying chambers were firstly assumed. The brick pile was considered as consisting of several thin layer beds. The simulation program calculated the brick and the air temperature based on the fixed bed model, layer by layer. The iteration continued until the convergence and continuity of the brick and air temperature were achieved. The firewood burning was put out when the bottom layer temperature in the firing chamber reached 650 °C. However, at this moment if the bricks in the cooling chamber are still at a temperature higher than 90 °C (the assumed maximum unloading temperature), the cooling

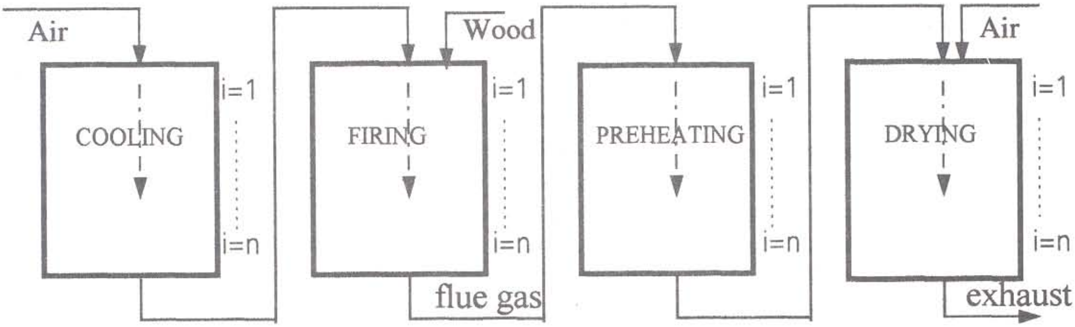

Fig. 8. Physical model of simulation.

process is going on, but now includes the former firing chamber as well. However, the air will be channeled bypassing the preheating chamber in order to maintain its high temperature. The cooling time in the successive cycle is, therefore, shortened because the bricks are already precooled. The processing times of the four processes are matched and, as a consequence, are alternately long and short.

3.2 Time Matching in Operation

Results of firing 2600 bricks at 800 °C with an air flow rate of 1000 kg/h appeared as two (sub)cycles, Fig. 9. The processes in the first cycle represent the condition when the four chambers are functioning simultaneously for the first time. Although the first cycle requires 28 h to finish, the firing time is only 5 h (18% of the cycle time). Within the firing period of 5 h, the bricks in the bottom layer of the drying chamber increase their temperature from 36 °C to 89 °C (A B in Fig. 9) while the temperature of those in the preheating chamber increases from 120 °C to 450 °C (CD). Similarly, the bottom layer of bricks in the firing chamber is heated from (the preheated temperature) 450 °C to 651 °C (EF). The preheating of the combustion air by the brick cooling process brings the bottom layer temperature (of the bricks) in the cooling chamber from 651 °C down to 478 °C (GH). Since the final brick temperature at the bottom layer should be at, say, 90 °C (the top layer bricks will be less than 90 °C), the cooling of bricks must be continued. The air continues to flow through the cooling chamber and also the former firing chamber. At the end of the first cycle, the bricks in these two chambers are cooled down to 89 °C (HI) and 193 °C (FJ), respectively. After leaving the former firing chamber, the air is channeled into the drying chamber to further remove the moisture, if still any. The air temperatures leaving the cooling chamber and the former firing chamber are given by lines WX and YZ in Fig. 9, respectively. At about 10 h the air temperature entering the drying chamber (process YZ) has a temperature of less than 150 °C (Y'), the fresh air mixing (to adjust the drying air temperature to a constant 150 °C) is not needed any longer. It is anticipated also that at this stage the green bricks are already dried. Therefore, it is assumed that the final brick temperature in the drying chamber at the end of the first cycle (28 h) is equal to the air temperature of 63 °C (K). Simultaneously, the conduction heat loss in the preheating chamber brings the brick temperature from 450 °C down to 351 °C (DL) which becomes the initial temperature of the firing in the second cycle.

In the second cycle the firing time is 6 h (LM) which is one hour longer than that of the first cycle, because the initial temperature in the firing chamber is lower (351 °C vs. 450 °C). It can, therefore, be anticipated that the second cycle consumes more firing energy. However, the cooling time of this cycle (JN) is much shorter than the previous one. At the end of the firing process, the temperature of bricks in the cooling chamber is 123 °C (N) which is, perhaps, acceptable for unloading or if a lower temperature is required, only a few hours of further cooling is needed. The bricks in the drying chamber are heated up to 93 °C (PQ) at the end of the firing process. The bricks at this condition (Q) should be sufficiently dried and ready for the preheating in the next cycle. It is interesting to note that the preheated bricks in the second cycle finish at a higher temperature of 494 °C (O) in comparison to 450 °C of the first cycle (D). Therefore, the third cycle requires a slightly shorter time for the firing (less firewood consumption), but the whole cycle time will be somewhat as long as the first cycle.

The above discussion gives a clear picture of time matching management and the associated temperature profiles of the bottom layer bricks in the four chambers. However, such quantitative discussion is limited to the conditions specified in Fig 9 only. For other conditions, the simulation data are given in Table 2.

In general, the more the load (number of bricks), the higher the energy is consumed per unit mass

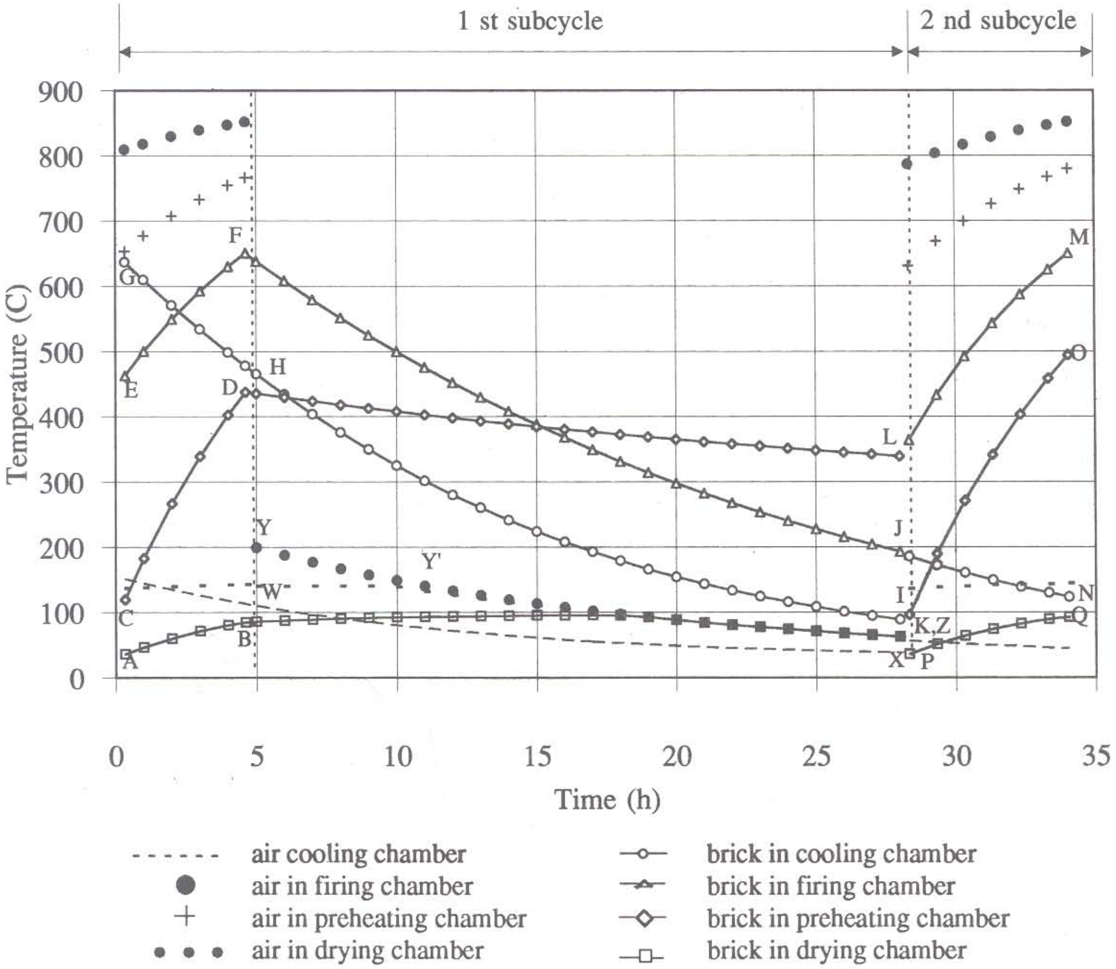

Fig. 9. Bottom bed brick temperature and outlet air temperature of the four chambers (firing temperature 900 °C, cooling air flow rate 1000 kg/h).

of the brick. For instance, at 900 °C firing temperature, the average specific energy consumptions for the first cycle of the 2200 brick, 2600 brick and 3500 brick firings are 1.380 MJ/kg, 1.514 MJ/kg and 1.651 MJ/kg, respectively. The corresponding figures for the second cycle are 1.840 MJ/kg, 2.138 MJ/kg and 2.406 MJ/kg. As a matter of fact, as the loading capacity of the kiln decreases, the operation of the system is brought close to the continuous tunnel kiln. It must be noted that the specific energy consumption in this simulation is higher than the value found in Part 2 [2]. This is caused by the differences in some assumptions, e.g., the kiln capacity, unit mass of brick, brick dimension, surface to volume ratio of the brick pile and brick orientation in the setting.

If a constant combustion air flow rate is applied, firing at higher temperature takes shorter time and consumes less energy. At a particular firing temperature, the increase of combustion air flow rate results in the increase of wood burning rate (Table 2) in order to maintain the required firing temperature. However, in doing this, the firing time is shortened. This results in the slight increase of

	Firing temperature (°C)	Combustion air flow rate (kg/h)	Subcycle 1					Subcycle 2			Overall cycle time (min)	Overall specific energy (MJ/kg)
			Time (min)			Specific energy (MJ/kg)	Wood consumption rate (kg/h)	Time (min)	Specific energy (MJ/kg)	Wood consumption rate (kg/h)		
			Fire & cool	Cool	Total			Fire & cool				
Kiln loading 2200 bricks	800	800	332	1068	1400	1.505	45.0	414	2.065	49.6	1814	1.785
		900	298	982	1280	1.526	50.9	376	2.113	55.8	1656	1.820
		1000	280	920	1200	1.599	56.7	340	2.125	62.1	1540	1.862
		1100	254	866	1120	1.599	62.6	318	2.190	68.4	1438	1.894
		1200	238	822	1060	1.640	68.4	294	2.210	74.7	1354	1.925
	900	800	238	1182	1420	1.279	53.4	304	1.795	58.7	1724	1.537
		900	224	1076	1300	1.360	60.3	272	1.810	66.1	1572	1.585
		1000	200	1000	1200	1.353	67.2	250	1.851	73.6	1450	1.602
		1100	192	928	1120	1.434	74.2	228	1.858	81.0	1348	1.646
		1200	180	880	1060	1.471	81.2	212	1.887	88.4	1272	1.679
	1000	800	192	1228	1420	1.207	62.4	236	1.620	68.2	1656	1.414
		900	172	1128	1300	1.220	70.5	216	1.673	77.0	1516	1.446
		1000	158	1062	1220	1.249	78.6	196	1.689	85.6	1416	1.469
		1100	152	988	1140	1.326	86.7	178	1.690	94.3	1318	1.508
		1200	138	922	1060	1.316	94.8	168	1.742	103.0	1228	1.529

Table 2. Operating time matching.

	Firing temperature (˚C)	Combustion air flow rate (kg/h)	Subcycle 1					Subcycle 2			Overall cycle time (min)	Overall specific energy (MJ/kg)
			Time (min)			Specific energy (MJ/kg)	Wood consumption rate (kg/h)	Time (min)	Specific energy (MJ/kg)	Wood consumption rate (kg/h)		
			Fire & cool	Cool	Total			Fire & cool				
Kiln loading 2600 bricks	800	800	430	1390	1820	1.622	44.1	576	2.427	49.3	2396	2.024
		900	393	1287	1680	1.677	49.9	520	2.467	55.5	2200	2.072
		1000	368	1192	1560	1.752	55.7	476	2.513	61.8	2036	2.132
		1100	348	1112	1460	1.830	61.5	440	2.558	68.0	1900	2.194
		1200	326	1034	1360	1.876	67.3	408	2.590	74.3	1768	2.233
	900	800	312	1528	1840	1.397	52.4	414	2.065	58.4	2254	1.731
		900	290	1390	1680	1.468	59.2	372	2.090	65.7	2052	1.779
		1000	274	1306	1580	1.548	66.1	342	2.138	73.1	1922	1.843
		1100	250	1210	1460	1.559	72.9	318	2.189	80.6	1778	1.874
		1200	234	1146	1380	1.596	79.8	294	2.210	88.0	1674	1.903
	1000	800	250	1610	1860	1.309	61.3	320	1.859	68.0	2180	1.584
		900	234	1466	1700	1.387	69.3	290	1.897	76.5	1990	1.642
		1000	220	1360	1580	1.455	77.4	264	1.921	85.1	1844	1.688
		1100	204	1276	1480	1.489	85.4	244	1.956	93.8	1724	1.722
		1200	190	1190	1380	1.517	93.4	226	1.978	102.4	1606	1.748

Table 2. Operating time matching (contd.).

	Firing temperature (°C)	Combustion air flow rate (kg/h)	Subcycle 1					Subcycle 2			Overall cycle time (min)	Overall specific energy (MJ/kg)
			Time (min)			Specific energy (MJ/kg)	Wood consumption rate (kg/h)	Time (min)	Specific energy (MJ/kg)	Wood consumption rate (kg/h)		
			Fire & cool	Cool	Total			Fire & cool				
Kiln loading 3500 bricks	800	800	640	2040	2680	1.766	43.5	876	2.729	49.1	3556	2.248
		900	584	1876	2460	1.823	49.2	788	2.766	55.3	3248	2.294
		1000	544	1736	2280	1.896	54.9	714	2.788	61.5	2994	2.342
		1100	506	1634	2140	1.948	60.6	654	2.812	67.7	2794	2.380
		1200	466	1534	2000	1.963	66.4	610	2.865	74.0	2610	2.414
	900	800	472	2228	2700	1.548	51.7	640	2.361	58.1	3340	1.954
		900	436	2044	2480	1.618	58.4	572	2.377	65.4	3052	1.998
		1000	396	1904	2300	1.639	65.2	522	2.413	72.8	2822	2.026
		1100	374	1786	2160	1.710	72.0	476	2.423	80.2	2636	2.066
		1200	348	1672	2020	1.742	78.8	442	2.457	87.6	2462	2.100
	1000	800	376	2364	2740	1.444	60.5	502	2.156	67.6	3242	1.800
		900	342	2178	2520	1.484	68.4	452	2.187	76.2	2972	1.836
		1000	314	2026	2340	1.520	76.3	410	2.207	84.8	2750	1.864
		1100	292	1888	2180	1.561	84.2	376	2.229	93.4	2556	1.895
		1200	276	1764	2040	1.616	92.2	346	2.239	101.9	2386	1.928

Table 2. Operating time matching (contd.).

the specific energy consumption if the bricks are fired with a high air flow rate. The firing time of the first cycle depends on the firing temperature (higher temperature, shorter firing time), but it is not the case of the total cycle time (of the first cycle) where the temperature independence is apparent. The processing time of the second cycle is significantly reduced in comparison to the total cycle time of the first cycle, particularly at the high firing temperature. However, the specific energy consumption of the second cycle is relatively higher. This phenomenon can be explained by the higher wood consumption rate due to the lower temperature of the combustion air (approximately 60 °C) compared to that of the first cycle (about 170 °C). In addition, the initial temperature of the bricks in the firing chamber is at lower temperature (states L vs E in Fig. 9). The firing time of the second cycle is, therefore, longer (Table 2).

Because the alternately long and short operating times of the two successive cycles are repeated, these two (sub) cycles can be considered together as the real production cycle. The last two columns in Table 2 give the overall cycle duration and the overall specific energy consumption which increase with the loading capacity. The kiln with 3500 brick capacity consumes about 0.4 MJ/kg - 0.5 MJ/kg more compared to the 2200 brick kiln, while the overall cycle time of the 3500 brick kiln is twice as long. This implies that the production rate of the 2200 brick loading is about 26% higher than the 3500 brick loading.

It is interesting to note that the same production rate can be achieved but at different specific energy consumptions if the firing temperatures and combustion air flow rates are different. For example, the kiln loaded with 2200 bricks and fired at 800 °C with 900 kg/h combustion air has the over all cycle time of 1656 minutes, which is equal to that required by the same kiln fired at 1000 °C and 800 kg/h combustion air. However, the specific energy consumption of the former is about 29% higher than that of the latter (1.820 MJ/kg vs. 1.414 MJ/kg). In terms of energy, it is suggested that the firing temperature should be high with a low air flow rate. However, in terms of the production rate, the firing temperature should be high with a high air flow rate. The brick productions in 14 days, which is the cycle time of the traditional updraft kiln of 70,000 brick capacity, for 800 °C and 1000 °C firing temperatures are given in Fig. 10. Firing 2,600 bricks at 800 °C yields the same production rate as firing 3,500 bricks at 1,000 °C. However, in order to minimize the unit cost (or the specific energy consumption), the latter should be employed (Table 2).

4. GENERAL DISCUSSION

Brick making is a very simple and primitive technique. However, at the present time, the kiln operation that meets the requirements of the brick making industry in developing countries is not so simple. There are special needs for this industry to be small for local consumption, batch operation to accommodate the fluctuation in demand and incorporate the waste heat recovery feature to reduce the energy consumption. The four-chamber kiln to serve the four functions simultaneously and cooperatively is not a new concept. Bull's trend kiln with many more chambers, normally used in a very big factory, is an example of this concept. However, the theoretical study on the four cooperative processes of the four chambers has never been reported until recently [2]. In this paper, the experimental verification was carried out and the time matching operation of the kiln cycles was thoroughly studied.

The conceptual design of the kiln in this study was based on the continuous moving fire kiln similar to the Bull's trend kiln. The continuous process, generally associated with a very long kiln, e.g., the tunnel kiln, cater to the lengthy and time-consuming cooling process. The Bull's trend kiln

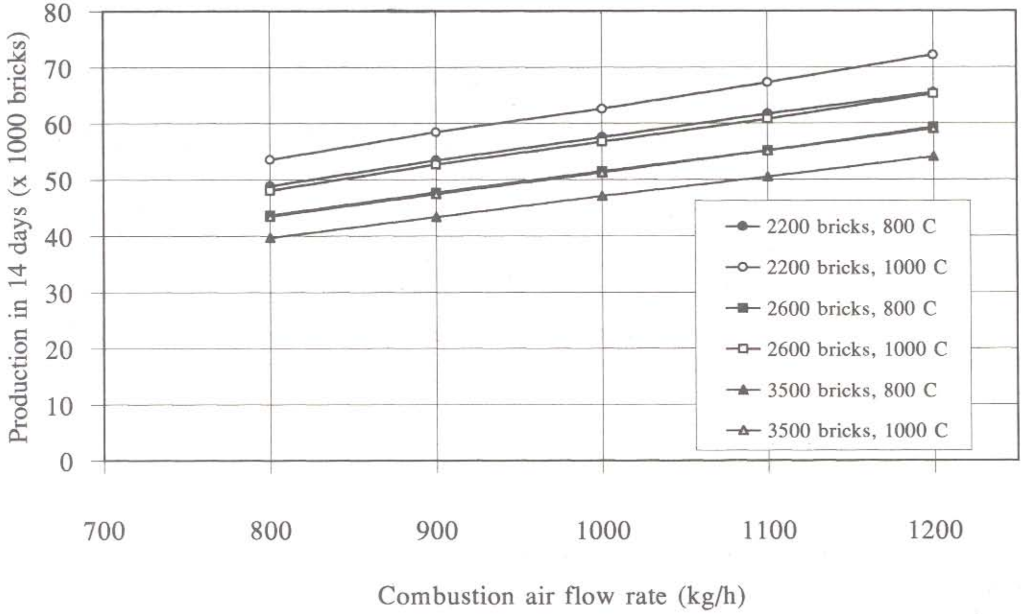

Fig. 10. Production in 14 days of different operating conditionsa.

is, therefore, a very big kiln with a capacity of millions of bricks [4]. It appears in a circular of elliptical loop formed by digging into the soil. The four-chamber kiln in this study is actually a compact above-ground Bull's trend kiln. Its compact size is achievable by matching the operating time and manipulating the flow of the hot gas.

In the South of Thailand the bricks are being fired in big updraft-open-top kilns. The normal capacity is 70,000 bricks and the batch cycle is 14 days. Furthermore, it needs many workers during a few days of loading and unloading. The specific energy consumption of these updraft kilns is 4 MJ/kg - 5 MJ/kg [3]. Such production rate (70,000 bricks in 14 days) can be achieved by the four-chamber kiln loaded with 2200 bricks, fired at 900 °C and a combustion air flow rate of 1200 kg/h (calculated from Table 2). Not only that the kiln provides a steady work for a smaller number of laborers, is smaller in size but not in production rate, requires less investment cost and land used for the factory, but it also consumes only half of the energy normally required by the traditional big updraft kiln. As the energy contributes up to 30% of the brick production cost [3] and the firewood price must compete with the rubber wood furniture factories in the region, the four-chamber kiln is a promising energy-efficient brick kiln.

5. CONCLUSION

A study toward energy saving in brick making was carried out systematically. After the key parameters for energy saving were identified and the processes in the kiln were clearly understood by the two papers published previously, this paper presented the experimental verification and the time matching operation. The experimental results of the single chamber kiln have proved the simulation of the four processes occurring in the four-chamber kiln. The operating time matching of the four processes was studied by computer simulation and established an operating guide line for the four-chamber kiln. The four-chamber kiln working cooperatively is the basic concept of the new type of the kiln being constructed and tested at the Prince of Songkla University. It is believed that this type of kiln can substitute the traditional inefficient updraft kilns and its high efficiency can solve the energy shortage problem presently faced by the brick making industry in most developing countries.

6. ACKNOWLEDGMENT

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