STUDY OF TRANSVERSE TEMPERATURE GRADIENTS IN ROLLER KILNS UNDER DIFFERENT OPERATING CONDITIONS

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ABSTRACT

The study was carried out with a measuring device developed by ITC, which allows transverse temperature distribution to be measured in the region beneath the roller plane, in different parts of the kiln. The resulting temperature measurement is much closer to actual tile temperature than the measurement obtained by the traditional method, which involves a fixed array of thermocouples arranged throughout the kiln. The temperature measurements found with both systems are compared, and the new measuring system is shown to yield data that monitor the actual firing schedule much more closely than the information provided by the traditional system.

Transverse temperature profiles beneath the roller plane are presented at different points in the kiln, and subsequently discussed. The effect is analyzed of the number of operating burners, combustion air flow rate, and gas static pressure in the kiln on the transverse temperature gradients.

1 INTRODUCTION

One of the principal stages in ceramic floor and wall tile manufacture is the firing stage, since it is in this stage that the physico-chemical transformations arise in the glaze and body, which provide the final product with its definitive properties.

Therefore, as tile quality is irreversibly fixed on firing, it is also the last process stage in which defects that may have arisen in foregoing stages can be repaired.

Firing ceramic tile currently takes place by fast twice or single firing in roller kilns. The heat supplied to the tile raises tile temperature. If the heat flow is uniform, the aesthetic and technical characteristics of the final products will also be uniform, thus enhancing quality, which is why heat transfer to the tile, and resulting tile temperature, should be uniform at each transverse section of the kiln.

Current temperature measuring systems in roller kilns do not provide enough data on transverse temperature differences in the firing chamber, as only one single point is measured in the cross sections at which they are located.

The Instituto de Tecnología Cerámica (ITC) has designed and patented a measuring system that allows determining transverse temperature differences under the roller plane, at any roller kiln section [1]. The data provided by this measuring system allow determining how roller kiln operating conditions impact transverse temperature differences.

The study, conducted at several roller kilns belonging to TAULELL, S.A., which are used for single-fired wall and floor tile manufacture, has been a collaborative undertaking involving TAULELL, S.A. and ITC technicians.

2 OBJECTIVES

The objectives may be summarized as follows:

- analysis of the data obtained on determining the transverse temperature gradients at different points in the roller kiln;

- study of how the different kiln operating conditions affect transverse temperature profiles.

3 MEASURING SYSTEM

The characteristics of the measuring system employed in the study have been detailed in foregoing papers [2], so that only a brief description will be given here.

The system consists of a metal roller, with a slightly smaller diameter than that of the rollers used in the roller kilns at which the measurements were carried out. The metal roller contains several thermocouples, whose number and type depend on the targeted data and working temperatures involved.

The transverse temperature distribution in any section of the kiln can be obtained by replacing the kiln roller at that point by the metal roller fitted with the thermocouples. Owing to the proximity of the active part of the thermocouples to the tile surface, the resulting temperature measurement is much closer to actual tile temperature than the one registered by the fixed kiln thermocouple. In the study, the mean value of the temperatures measured by the sensing roller at different points in the kiln is termed the tile mean temperature (T_{tile}).

The results obtained, as well as the methodology adopted in the study are generally applicable to other single-layer roller kilns. However, the considerable influence of each individual kiln construction and operating conditions on transverse temperature differences means that some of the findings cannot be directly extrapolated to every roller kiln.

4 DETERMINATION OF TRANSVERSE TEMPERATURE DIFFERENCES UNDER THE ROLLER PLANE IN DIFFERENT PARTS OF THE KILN

Transverse temperature distribution under the roller plane was determined in different parts of the kiln, using the usual operating conditions, by means of the sensing roller. This was done by placing the sensing roller at a point just above the fixed kiln thermocouples that monitor kiln temperatures under the roller plane. Kiln temperature was measured while wall tile was being fired.

After positioning the roller at the measuring point, the evolution of the temperature was monitored in real time at each thermocouple within the roller. The temperature rose sharply at the start until it stabilized. The temperature distribution in a given kiln section was found by averaging the temperatures measured by each thermocouple, once these temperatures had stabilized.

Table 1 lists the temperatures measured by each sensing roller thermocouple in various parts of the kiln. The table also details the maximum temperature differences in each section (ΔT_{max}), mean tile temperature (T_{tile}), temperature measured by the fixed kiln thermocouple located beneath the roller plane in each studied section (T_{kiln}), and the difference between these last two measurements (ΔT).

Table 1. Temperatures (°C) measured in different cross sections of the kiln.

L(*) (cm)	Distance (D) from kiln entrance (m)												
	19	21	23	25	27	31	33	35	37	39	41	43	45
5.7	880	914	928	958	991	1082	1118	1114	1114	1122	1118	1089	1064
15.7	857	890	905	942	988	1102	1130	1121	1119	1126	1122	1086	1059
25.7	847	884	894	934	986	1116	1140	1127	1122	1130	1126	1082	1053
35.7	852	887	895	936	989	1121	1141	1128	1123	1130	1127	1081	1054
45.7	875	905	913	948	994	1115	1133	1127	1122	1129	1128	1085	1058
55.7	855	886	897	937	990	1124	1140	1130	1124	1131	1129	1083	1055
65.7	855	886	898	937	989	1125	1140	1131	1125	1132	1130	1083	1055
75.7	864	893	905	942	991	1125	1139	1132	1125	1132	1131	1083	1055
85.7	858	890	901	939	991	1125	1140	1132	1125	1132	1130	1081	1054
95.7	858	890	901	939	991	1125	1140	1132	1125	1132	1130	1081	1054
105.7	865	895	902	939	992	1127	1140	1131	1125	1132	1130	1080	1056
115.7	876	902	910	947	992	1120	1133	1128	1124	1130	1129	1084	1058
125.7	860	886	896	936	989	1123	1140	1131	1125	1131	1130	1080	1050
135.7	860	886	896	936	989	1112	1130	1130	1125	1129	1126	1081	1051
145.7	882	911	920	953	988	1095	1117	1122	1125	1125	1122	1087	1053
	PREHEATING					FIRING							
ΔT_{max}	35	30	34	24	5	45	24	18	11	10	13	9	11
T_{tile}	863	895	905	942	990	1114	1134	1127	1123	1129	1127	1084	1056
T_{kiln}	945	-	945	-	1015	1120	-	1121	1123	1125	1110	1050	1033
ΔT	-82	-	-40	-	-25	-6	-	+6	0	+4	+17	+34	+23

(*) Distance from the thermocouples to the kiln wall

4.1 DIFFERENCES BETWEEN THE TEMPERATURES MEASURED BY THE KILN THERMOCOUPLES (T_{KILN}) AND MEAN TILE TEMPERATURE (T_{TILE}).

Figure 1 shows a plot of the temperature measurements recorded by the kiln thermocouples located beneath the roller plane (T_{kiln}), mean tile temperature (T_{tile}) and the difference between both, at different transverse sections of the kiln (ΔT).

It can be observed in the figure that mean tile temperature in the preheating zone lies below ambient temperature. The difference decreases as the tile advances towards the firing zone, and virtually disappears in the peak firing zone. In the following zone, tile temperature remains higher than ambient temperature as the set kiln temperature falls.

The difference between tile and ambient temperature stems from the thermal inertia of the tile as a result of the high heating and cooling rates. Figure 1 shows that at low or zero heating rates (peak firing zone), tile and ambient temperature differences decrease.

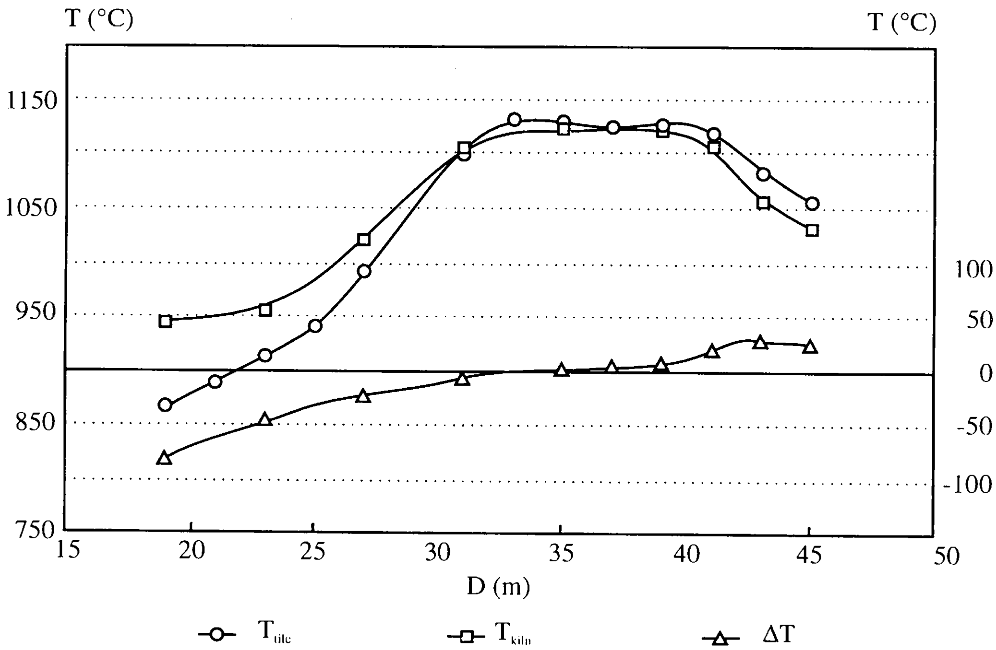

Figure 1. *Difference between mean tile temperature and the temperature measured by the kiln thermocouples beneath the roller plane.*

4.2 TRANSVERSE TEMPERATURE DISTRIBUTION IN THE PREHEATING ZONE

The transverse temperature profiles corresponding to different sections of the studied kiln's preheating zone have been plotted in Figure 2, using the values detailed in Table 1.

The figure also shows that there is non-uniform temperature distribution in every kiln cross section. The maximum differences in each section, which are large at low temperatures (35°C at 19 m from kiln entrance), decrease as temperature rises.

The temperature profiles also exhibit concave regions, which coincide with the position of the tile. In this part, ambient temperature is higher than tile temperature, and the tile heats up from the edges inwards. In the preheating zone, the centre of the tile is therefore colder than the edges.

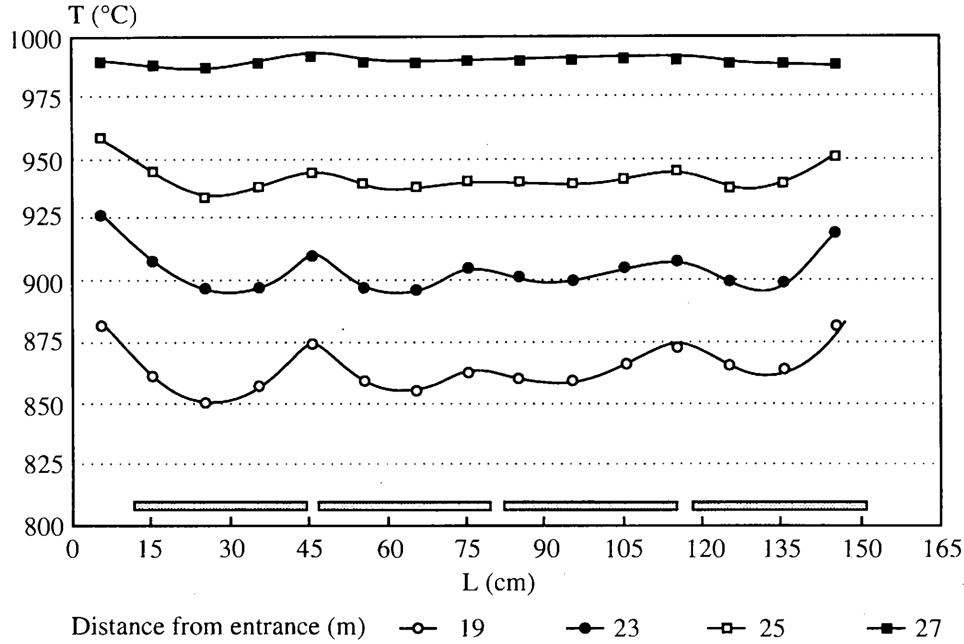

***Figure 2.** Transverse temperature profiles in the preheating zone under the roller plane.*

4.3 TRANSVERSE TEMPERATURE DISTRIBUTION IN THE FIRING ZONE

Figure 3 depicts the measured transverse temperature profiles in the firing zone. It can be observed that these profiles do not all exhibit the same shape across the whole firing zone. At the start (31 to 41 m), the temperature in the areas close to the walls and in the spacings between the tiles is lower. These differences decrease as the tile approaches peak temperature. The former feature, contrary to what occurred in the preheating zone, is likely to be due to an increase in wall heat losses in this area, mainly as a result of the high temperatures involved.

In the last firing areas (43 to 45 m), the drop in temperature (Figure 1) gives rise to a tile temperature distribution in which tile edge temperatures lie slightly higher than tile centre temperatures. This situation allows repairing faults relating to the flatness of tile edges, since a significant difference in temperature is set up between the edges and centre of the tile in high temperature areas, as a result of which tile can undergo dimensional changes.

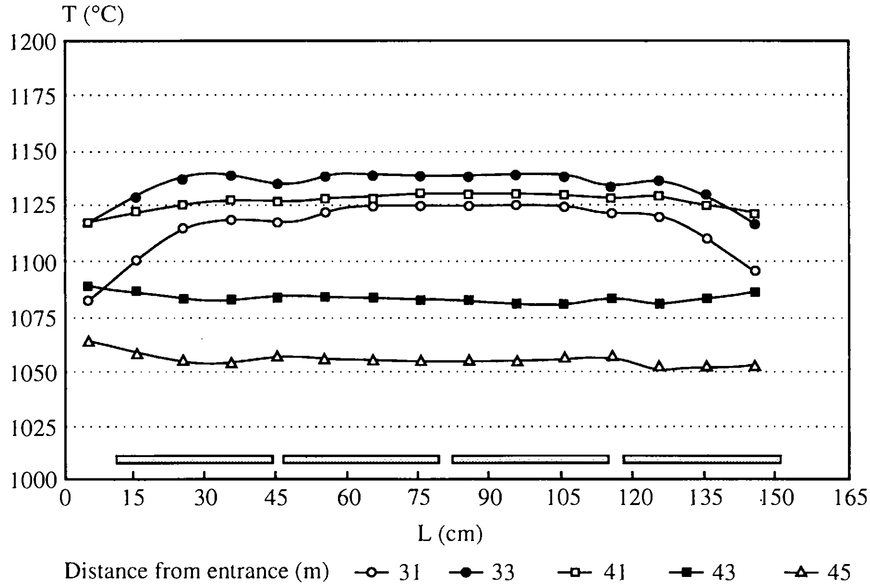

Figure 3. Transverse temperature profiles in the firing zone under the roller plane.

4.4 ANALYSIS OF THE ACTUAL TILE FIRING CYCLES ACCORDING TO TILE POSITION IN THE KILN

Once the transverse temperature distributions under the roller plane in the different cross sections of the kiln have been determined, the real firing cycles that a tile undergoes can be established as a function of its position in the row. Thus, using the data from Table 1, the heat-treatment cycles were plotted in Figure 4 to which the tile side closest to the left kiln wall (T_{left}), the tile side closest to the right kiln wall (T_{right}), and the centre of the tile in the middle of the kiln (T_{centre}) were subjected during firing. The temperature differences between the tile located at each side (areas closest to the walls), and the centrally positioned tile (kiln centre) have been plotted at the bottom of the figure.

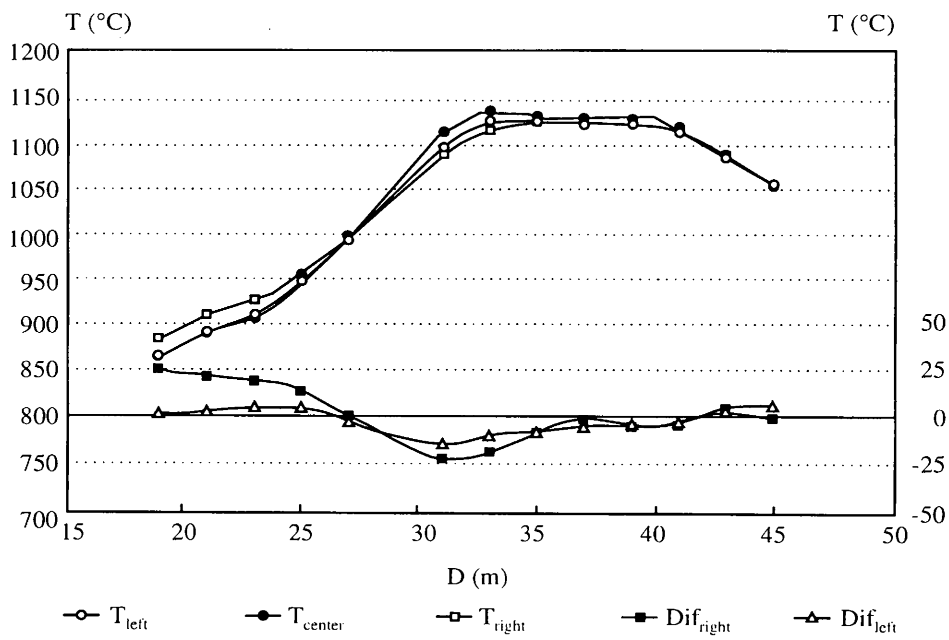

Figure 4. Heat-treatment cycles of the tile edges fired next to the kiln wall and of the tile centre fired in the middle of the kiln.

The heat-treatment cycle that each respective part of the tile undergoes is shown to differ. Whereas in the first preheating zone area (17 to 27 m) the temperature of the tile on the right exceeded that of the other two tiles (differences of up to 25°C), in the travel through the preheating and initial firing zone (27 to 32 m), the tile next to the walls underwent the lowest heat treatment. Finally, in the firing zone, the three tile domains involved were subjected to virtually identical heat-treatment cycles.

The tile being fabricated at this kiln was porous wall tile. Dilatometric analysis showed that the bodies used for this type of product exhibit rapid shrinkage in the temperature range 800-925°C. It is then often the extent of the arising shrinkage that will produce wedging or curvature in the fired tile [3]. As Figure 4 shows, in this critical temperature interval, the temperature of the tile fired on the right was higher than that of the other tiles in the row, which yielded different final curvatures, impairing overall finished product quality of the production batch.

5 INFLUENCE OF THE VARIATION OF SOME KILN OPERATING CONDITIONS ON TRANSVERSE TEMPERATURE GRADIENTS UNDER THE ROLLER PLANE

The measuring system was used to determine transverse temperature gradients under the roller plane in a series of experiments aimed at assessing how the main kiln operating conditions impacted such gradients. The results are set out below of the experiments involving the factors or conditions that most affected transverse temperature distribution in the firing chamber, namely:

- Number of lighted burners
- Combustion air static pressure
- Gas static pressure in the kiln

These experiments were carried out in the roller kiln while stoneware floor tile was being fired.

5.1 EFFECT OF THE NUMBER OF LIGHTED BURNERS ON TRANSVERSE TEMPERATURE PROFILES

To analyze how the number of lighted burners affected transverse temperature gradients beneath the roller plane, the sensing roller was placed in the preheating zone, in the middle of an array of 8 burners, four of which were positioned on each side of the kiln, and whose operation was regulated by a single control thermocouple.

Two experiments were run, alternately switching off two burners on each side of the kiln, as illustrated in Figure 5, resulting in a staggered burner arrangement.

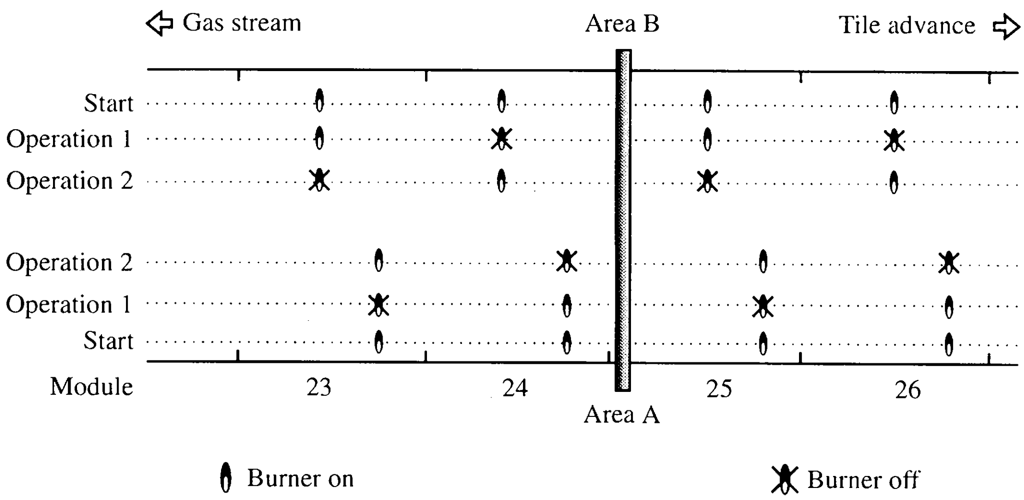

Figure 5. Detail of the tested burner arrangements beneath the roller plane

To determine how burner operation evolved during testing, it was necessary to take into account the natural gas pressures at each burner, detailed in Table 2, under the different operating conditions.

Table 2. Static natural gas pressure at the burners (mmca.) during the experiments

	Area A				Area B			
Module	23	24	25	26	23	24	25	26
Start	34	34	27	36	30	26	38	36
Operation 1	-	69	-	70	62	-	76	-
Operation 2	82	-	81	-	-	64	-	80

It may be inferred from the data in Table 2, that when a number of the initially lighted burners was turned off, the ones that kept operating raised their output in order to hold the set temperature. Figure 6 depicts the evolution of the transverse temperature profiles in the measuring area during the experimentation.

In operation 1, the temperature rose in area B and dropped in area A. This was the result of turning off a number of burners, which was compensated by a flow of hotter gas from the burner located at module 25 in area B (Figure 5), which raised temperature in this area. The opposite happened in area A: the burner in module 25 was turned off (Figure 5) and the flow of cold gases therefore lowered this area's temperature. The same explanation applies to operation 2, yielding an opposite effect.

On turning off these burners, the temperature profile was altered throughout the whole measuring area, with temperatures swinging round an invariable point, apparently coinciding with the position of the control thermocouple (solid black dot on the abscissa axis of Figure 6).

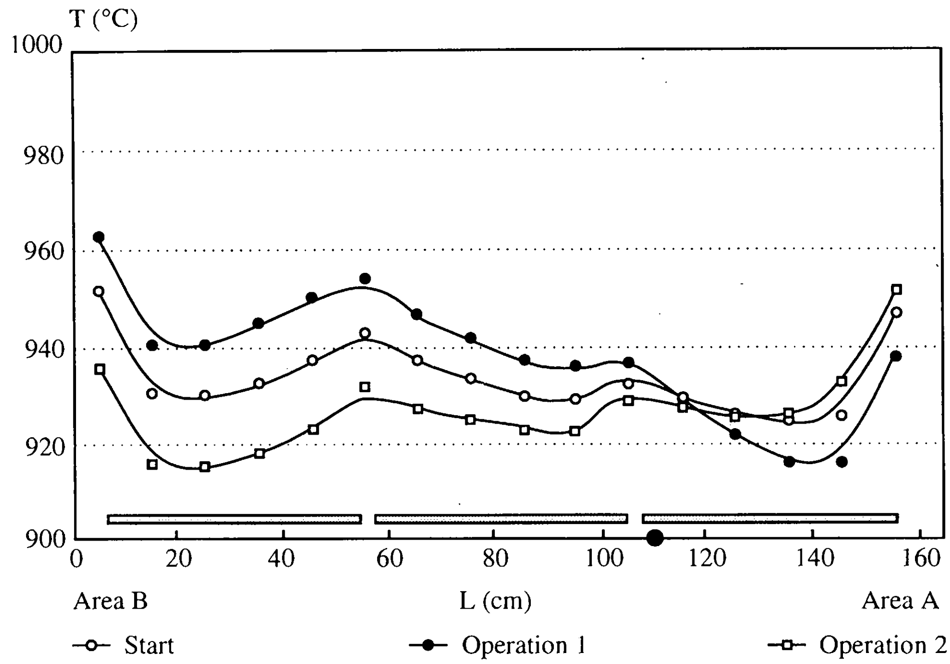

Figure 6. *Transverse temperature profiles at the measuring point on modifying the number of operating burners.*

The experiments showed that the transverse temperature distribution at a given point largely depended upon the operating conditions of the area lying before it, as a consequence of the direction of the gas stream in the kiln. It may be observed in Figure 6 that in the studied area, when the burners were switched off in a staggered arrangement, the temperature gradient rose, since the temperature drop in one area had to be compensated by an increase in the adjacent one, in order to hold the temperature steady in the area around the control thermocouple.

5.2 EFFECT OF BURNER COMBUSTION AIR PRESSURE ON TRANSVERSE TEMPERATURE GRADIENTS.

This experiment was conducted by placing the sensing roller in the preheating zone, in the centre of an array of eight burners, whose combustion air pressure was modified.

As it is sometimes necessary to act solely upon the temperature of one part of the kiln, it was decided to study separately the effect of combustion air pressure of the burners located on the right and on the left side of the kiln. Standard combustion air pressure at the burners in this area was 55 mmca., which was modified to yield values of 40 and 100 mmca.

5.2.1 Modification of burner combustion air pressure on the left side of the kiln.

The transverse temperature profiles found on modifying the combustion air pressure of the burners located on the left side off the kiln have been plotted in Figure 7. The figure shows that on raising burner combustion air pressure, the temperature in this area dropped, while virtually remaining steady on the opposite side.

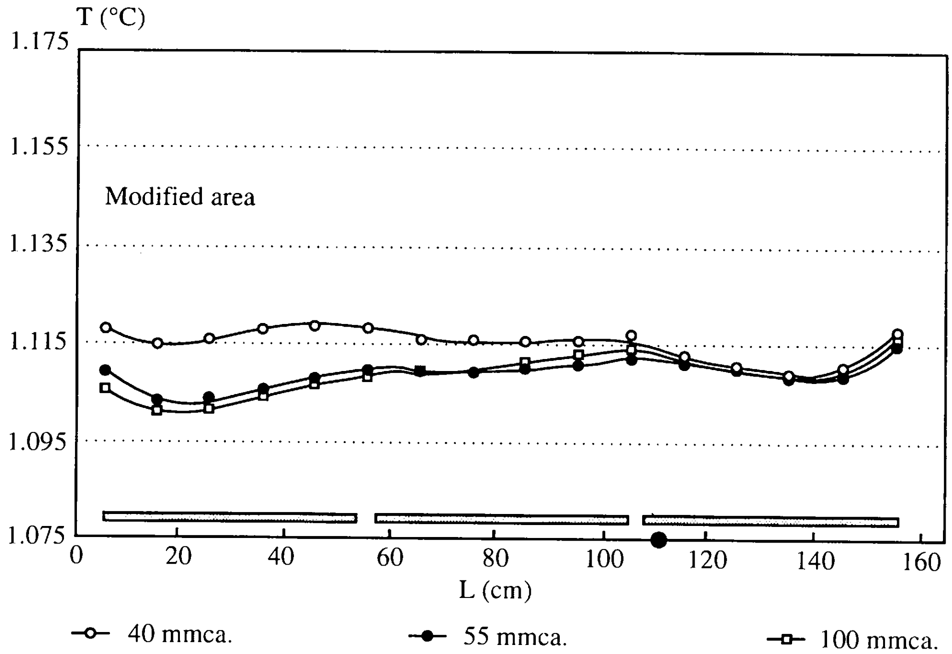

Figure 7. Transverse temperature profiles obtained on modifying burner combustion air pressure on the left side of the kiln.

This effect is due to the fact that the control thermocouple that regulates burner operation is located on the right side of the kiln (solid black dot on the abscissa axis in Figure 7). As the modifications did not affect temperature in that area, burner operation remained unaltered. The rise in the combustion air flow rate thus produced local cooling, which may be useful at times when the transverse temperature distribution is to be modified.

Table 3 details the measured temperatures as well as the maximum temperature differences found at the different tested combustion air pressures. Mean temperature was slightly modified on changing the combustion air flow rate, because the kiln control thermocouple was unable to detect or control this modification. Table 3 shows how in this case, the transverse temperature gradient rose slightly on increasing combustion air pressure.

Table 3. Maximum temperature differences and mean temperatures found in each experiment.

Combustion air pressure (mmca.)	T_{tile} (°C)	ΔT_{max} (°C)
40	1115	11
55	1109	13
100	1108	16

5.2.2 Modification of burner combustion air pressure on the right side of the kiln

The transverse temperature profiles obtained on modifying burner combustion air pressure on the right side of the kiln have been plotted in Figure 8. It can be observed that when combustion air pressure was raised, the temperature decreased in the area involved. However, contrary to what happened in the foregoing experiments, the temperature on the left side of the kiln also changed.

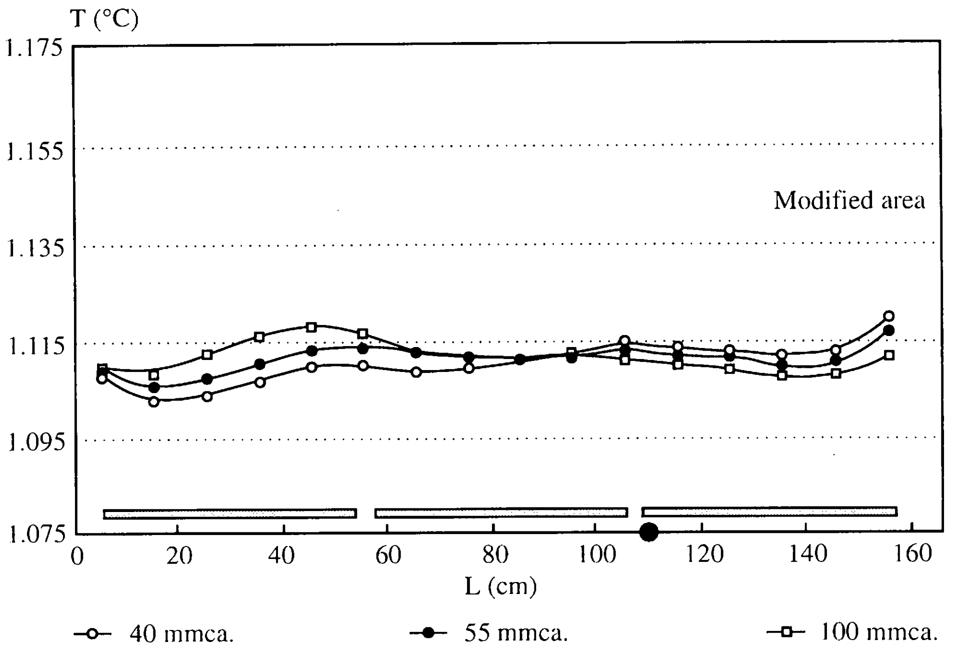

Figure 8. *Temperature profiles obtained on modifying burner combustion air pressure on the right side of the kiln.*

This occurred because the control thermocouple regulating burner operation was located on the right side of the kiln (black dot on the abscissa axis in Figure 8). The experimental operations altered the temperature in this area, causing the output of this whole set of burners to change. The rise in combustion air flow rate produced local cooling in the modified area. As such cooling was detected by the control thermocouple, this whole section temperature profile was altered in order to keep the temperature steady around the control thermocouple.

Table 4 details mean temperatures and maximum temperature differences at the different tested combustion air temperature pressures. In this case, mean temperature was not modified on altering the combustion air flow rate, since the kiln control thermocouple detected the temperature change and controlled it. The table also shows that the transverse temperature gradient decreased slightly on raising combustion air pressure.

Table 4. *Maximum temperature differences and mean temperatures found in each experiment.*

Combustion air pressure (mmca.)	T_{tile} (°C)	ΔT_{max} (°C)
40	1111	19
55	1112	13
100	1112	12

It was thus shown that modifications in the combustion air flow rate noticeably affected the transverse temperature gradient in the kiln. The extent of this effect depended upon the position of the burners relative to the control thermocouple. In the tested air pressure interval in the kiln area involved (preheating zone), raising burner combustion air pressure on one side of the kiln caused the temperature on that side to drop. When the control thermocouple was located in that area, the whole transverse temperature profile altered.

However, when the control thermocouple was located on the opposite side, the temperature only changed on the side where the combustion air flow rate was modified.

5.3 INFLUENCE OF GAS STATIC PRESSURE IN THE KILN ON TRANSVERSE TEMPERATURE GRADIENTS.

When tile defects relating to non-uniform temperature distribution appear, it is common practice to raise gas static pressure in the kiln. This increase seems to reduce preferential gas circulation currents, producing more uniform temperature distribution.

To study how gas static pressure in the kiln affects transverse temperature gradients, a sensing roller was placed in the kiln firing zone. Kiln operating conditions were adjusted, and the maximum gas static pressures were set at 0.3, 0.6 and 0.85 mmca. The transverse temperature distributions found at these three static pressures have been plotted in Figure 9.

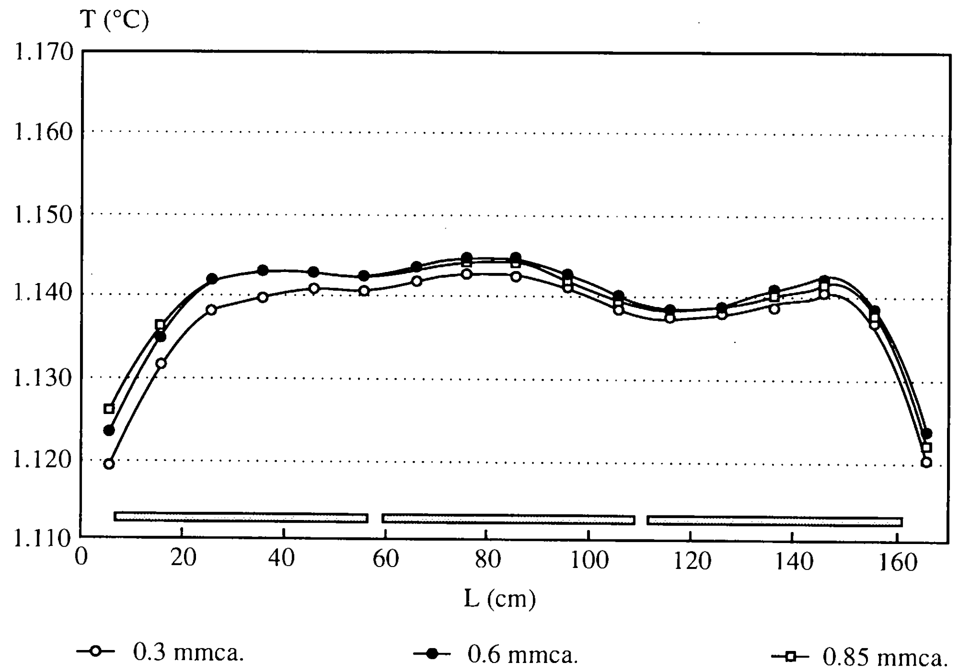

Figure 9. Variation of transverse temperature gradients on modifying gas static pressure in the kiln.

Table 5 sets out mean temperatures and maximum temperature differences at each tested pressure.

Table 5. Maximum temperature differences and mean temperatures found in each experiment.

Static pressure (mmca)	T_{tile} (°C)	ΔT_{max} (°C)
0.3	1138	24
0.6	1140	22
0.85	1141	19

An analysis of the data shown in Figure 9 and Table 5 indicates that raising gas static pressure in the kiln slightly lowers the maximum transverse temperature difference and slightly increases mean tile temperature.

6 CONCLUSIONS

It is first of all necessary to point out that all the transverse temperature gradients obtained in this study were determined below the roller plane, as a consequence of the measuring system involved. Thus, the inferences drawn from the study always refer to how the different experimental operations affected this region of the kiln. The effect of these operations can sometimes be directly transferred to the kiln region above the roller plane, but in certain cases this may not be possible.

The following conclusions may be drawn from the study:

- Temperature determination at one point in a kiln cross section, as has been standard practice to date, provides no useful data regarding the transverse temperature gradient in a kiln.

- The differences between tile and ambient temperature decreased on reducing the heating rate and raising gas static pressure within the kiln.

- In the preheating zone, temperatures in areas close to the kiln walls were higher than in the centre, possibly owing to ambient temperature being higher than that of the tile.

- In the firing zone, temperatures in areas close to the kiln walls were lower than in the centre. This may be due to wall losses as a result of the high gas temperature.

- On turning off some burners, in the staggered arrangement tested in this study, the temperature gradient increased in the firing chamber, as a consequence of the rise in heating output by the other burners in order to hold the set temperature.

- The modification of combustion air pressure at the burners greatly affected kiln transverse temperature distribution. Its effect largely depended upon the position of the modified burner relative to the control thermocouple.

- Raising static pressure within the firing chamber slightly lowered transverse temperature differences in the firing zone, concurrently increasing mean tile temperature, probably due to increased heat transfer by forced convection as a result of this operation.

7 REFERENCES

[1] AICE. Procedimiento y equipo para determinar la distribución de temperaturas en máquinas térmicas con sistemas de rodillos para transporte del producto. Spain. *Patent no. 94/00936*, 1994-05-04.

[2] FERRER, C.; LLORENS, D.; MALLOL, G.; MONFORT, E.; MORENO, A. Optimización de las condiciones de funcionamiento en hornos monoestrato. (III) Medida de gradientes transversales de temperatura. *Técnica Cerámica*, 227, 653-662, 1994.

[3] AMORÓS, J.L.; ESCARDINO, A.; SÁNCHEZ, E.; ZAERA, F. Stabilità delle dimensioni nelle piastrelle porose monocotte. *Ceramica Informazione*, 324, 56-67, 1993.1