IMPROVEMENT OF THE DISTRIBUTION OF THE QUANTITY OF GLAZE IN BELL WATERFALL APPLICATION SYSTEMS

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ABSTRACT

Bell waterfall glazing systems have always been characterised by providing a non-uniform glaze deposition on the tile surface owing to the circular shape of the resulting curtain of glaze. This characteristic, which becomes more pronounced as the dimensions of the bell diameter and tile width approach each other more closely, sometimes leads to defects relating to variations of shade in the end product.

In this study, the constructive form of a patented bell waterfall glazing system [1] has been optimised with a view to minimising the differences in the quantity of glaze applied between the sides and the centre of the ceramic tiles. The study was rounded off with pilot-scale trials that validated the correct operation of the device.

1. INTRODUCTION

One of the most widespread defects in the ceramic tile manufacturing process, which significantly impairs end product quality, is non-uniform colour between tiles of the same model and in the same tile. Numerous studies [2][3][4][5] have shown that this defect stems, on the one hand, from a lack of stability in the physico-chemical properties of the materials involved in the decoration process (body, engobe, glaze, ink, etc.) and, on the other, on the inappropriate performance of the manufacturing process stages: essentially application of the engobe, glaze, decorations, and firing.

At present, bell waterfall glazing systems are widely used in ceramic tile manufacture. However, despite their simplicity and effectiveness, bell glazing displays a series of disadvantages that require thorough, continuous control of the glazing operation in order to assure end product quality. On the one hand, there is the sensitivity to viscosity changes in the glaze, which can lead to important variations in the quantity of glaze, known as 'grammage', deposited on the tiles. On the other hand, there are differences in the quantity of glaze deposited between the edges and the centre area of large-sized tiles as a result of the circular shape of the curtain of glaze [6].

In recent years, these disadvantages have led to good acceptance by tile manufacturers of linear curtain glazing systems, known in Spanish as velas or fileras. These systems solve the problems relating to the differences in the quantity of glaze applied on to the same tile and, in their more advanced versions, they can keep the applied glaze flow rate constant, independently of variations in glaze viscosity. Despite the progress made by linear deposition systems, the lower cost and greater simplicity of bell waterfall glazing still make this the most widely used system for engobe and ceramic glaze application.

Several studies have proposed solutions for addressing the problems related to the sensitivity of the discharge flow rate with regard to the variations in glaze viscosity. Particularly noteworthy are, for, instance a system for the continuous measurement of the glaze feed flow rate to the bell [7], which allows automatic regulation of the feeder flow control valve to assure a constant discharge flow rate. There is, further, an improved glaze feed system [8][9] in which, thanks to an optimised constructive design, glaze charge losses are minimised when the glaze flows through the system, the discharge flow rate being insensitive to variations in viscosity. However, despite these advances, no systematic study has to date been conducted that enables the problems relating to the differences in the quantity of glaze applied between the edges and the centre of the tiles to be minimised or solved.

The control method customarily used for correcting the differences in grammage on a tile consists of placing metal plates on the edges and the middle of the bodies to be decorated (generally one plate in the middle and two on each side), on which the glaze deposited on the different areas of the tile is collected. Comparison of the quantity of glaze collected on the metal plates then allows establishing whether it is necessary to perform some type of action on the bell level in order to attempt to correct the observed differences in grammage.

In most cases, when problems appear with relation to the glaze distribution on the tiles, the bell is tilted slightly in the direction of the falling curtain of glaze in order to favour the glaze flow over the centre of the tile and to increase the relative quantity of glaze that is applied on the middle of the tiles. On other occasions, some manufacturers increase the distance between the edge of the bell and the tile surface.

In any event, though these control actions notably improve glaze distribution on the decorated tiles, they continue to restrict the use of bells to tile sizes that are much smaller than the bell diameter. In addition, though the control action can produce good uniformity of the applied glaze layer under certain rheological conditions of the glaze composition, if a change occurs in the properties of the glaze, there is no assurance that glaze distribution will remain uniform. Indeed, if the bell is tilted until the distribution is equalised when there is a non-uniform distribution of the quantity of applied glaze, if there is a possible increase in viscosity, decreasing the deposited glaze flow rate will again change the glaze flow profile on the bell and the uniformity attained by the action will be lost.

2. OBJECTIVE

This study was undertaken to design and validate a new constructive form for the discharge edge of a bell waterfall glazing system, which would assure a uniform glaze distribution across the entire width of the tiles independently of the changes that might occur in the rheological properties of the glaze composition.

3. THEORETICAL FOUNDATIONS

3.1. Geometric analysis of the deposition of a circular curtain of glaze on the ceramic tile surface

From a geometric viewpoint, bells consist of a body of revolution obtained from a relatively complex curve. The ground plan of a bell exhibits a circular cross-section, such that the glaze suspension, after being fed on to the centre part of the bell, spreads radially across the bell surface so that, once it reaches the edge, it falls producing a circular curtain. In the middle of the bell, there is usually an overflow system that allows the glaze flow to be directed towards one side of the bell with a view to creating a semi-circular curtain like the one shown in Figure 1.


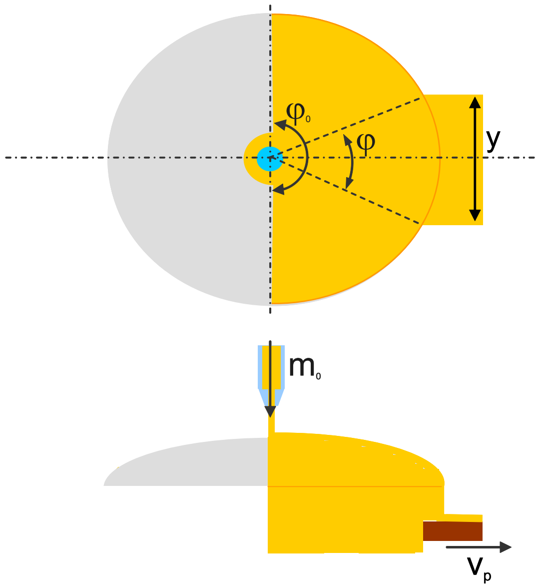

Figure 1. Semi-circular curtain of glaze produced with a conventional bell waterfall (left) and schematic illustration of the operation (right).

In order to obtain equations that relate the characteristic geometric parameters of a bell to the quantity of glaze applied in the different areas of the tile, an ideal bell like the one shown in Figure 1 is considered. Before determining the quantity of glaze applied on to the surface of a tile, it is necessary to define the glaze mass flow rate per unit angle, m_φ (kg/s rad), which is given by equation 1.

$$m_\varphi = \frac{m_o}{\varphi_o}$$

Equation 1

where m_o is the mass flow rate of the glaze discharged from the feeder (kg/s) and φ_o the angle covered by the glaze when it spreads over the bell (rad). In the case of the bell depicted in Figure 1, since a semi-circular curtain is involved, this angle becomes 180º.

If it is assumed that the bell is perfectly balanced so that the glaze flow fed into the middle of the overflow is uniformly distributed in a radial form, producing a semi-circular curtain, and the edge effects produced in the overflow are disregarded, m_φ may be considered constant and independent of φ. Using m_φ, the quantity of glaze deposited on the tile can be calculated when tile size and tile rate of advance are known. Indeed, the average mass flow rate of the applied glaze per transverse unit of the tile, $\overline{m}_p$ (kg/(s m)), for a tile (or fraction of tile) with a width 'y' (m), is given by equation 2.

$$\overline{m}_p = \frac{m_\varphi \varphi}{y}$$

Equation 2

in which φ is the angle of aperture of the curtain of glaze that is deposited on the tile, which can be calculated from equation 3.

$$\varphi = 2arcsen\frac{y}{r}$$

Equation 3

where r (m) is the bell radius. Thus, at a tile rate of advance v_p (m/s) and tile length 'x' (m), the quantity of glaze deposited on the tile, G (kg), would be obtained from equation 4.

$$G = \frac{\overline{m}_p}{v_p} yx$$

Equation 4

Finally, combining equations 1, 2, and 4 yields equation 5, which allows the quantity of glaze deposited on a tile to be calculated, when a mass flow rate m_o is fed to the bell.

$$G = \frac{m_o}{v_p}\frac{\varphi}{\varphi_o}x$$

Equation 5

According to this equation, the grammage applied on to a body solely depends on the rate of tile advance, tile size, and the angle relationship between the total angle of aperture of the curtain of glaze and the angle of the curtain deposited on the tile.

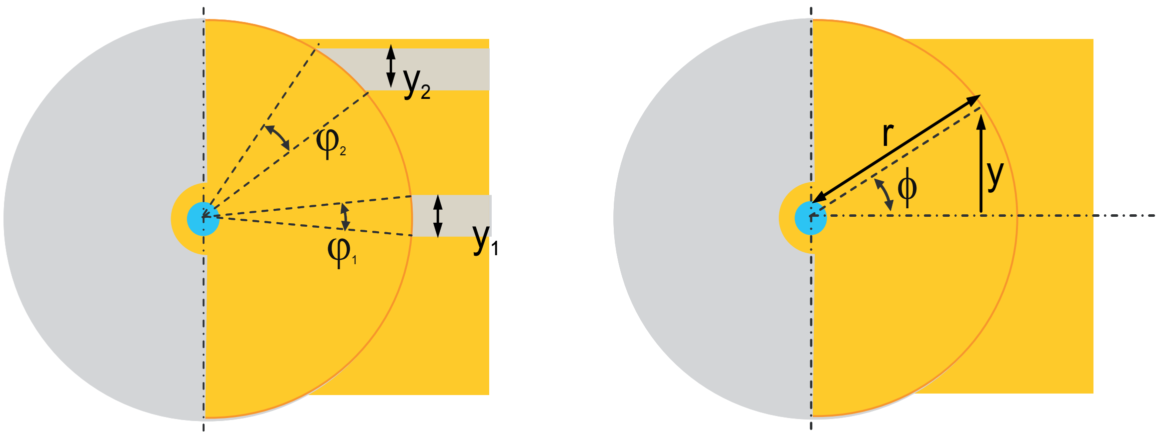

Figure 2. Angles of the curtain of glaze corresponding to different areas of a glazed tile (left) and characteristic geometric parameters of the discharge edge (right) in a round bell

The passage of a tile under a glazing bell is schematically illustrated in Figure 2, in which two longitudinal bands of the same width have been shaded on the surface of the tile. The mass flow rate of the glaze deposited by an element of the curtain of glaze, m_{pi}, of angle φ_i may be calculated as:

$$m_{pi} = m_{\varphi}\varphi_i$$

Equation 6

Since the angle of the curtain that deposits glaze on to the centre part of the tile, φ_1, is smaller than the angle of the curtain that deposits glaze on the tile side, φ_2, the quantity of glaze applied on to the centre of the tile is less than that deposited on the tile side. That is, the average mass flow rate of the glaze per unit tile transverse length, which is given by equation 2, is lower in the tile centre area than at the ends. This difference becomes more pronounced as the quotient between the bell diameter and the width of the decorated tile decreases: this is the reason that such bells can hardly be used for tile widths larger than 50% of the bell diameter.

3.2. Optimised bell geometry

With a view to assuring a uniform distribution of the quantity of glaze deposited on a tile, $\overline{m}_p$ needs to remain constant and not vary with the width of the tile, which means that the bell discharge edge cannot be circular but needs to adopt the form of a particular curve. In order to deduce the representative equation of that curve, it is necessary to define parameter r_o (equation 7) as the quotient between the glaze mass flow rate per unit angle and the mass flow rate of the glaze applied per tile transverse unit.

$$r_o = \frac{m_{\varphi}}{\overline{m}_p}$$

Equation 7

Since the distribution of the applied glaze will be uniform when $\overline{m}_p$ is constant, according to equation 7, if m_{φ} is assumed to be independent of the value of ϕ (see Figure 2), in order to satisfy the objective that $\overline{m}_p$ is constant, r_{θ} must also be constant. Thus, starting with equation 2, and taking into account the definition of m_{φ}(equation 1), equation 8 can be obtained.

$$r_o = \frac{m_o y}{\varphi_o m_{\varphi}\phi} = \frac{m_o y}{m_o \phi} = \frac{y}{\phi}$$

Equation 8

On the other hand, if 'r' is defined as the distance between the centre of the bell and the bell discharge edge, measured on the horizontal plane that passes through its centre (see Figure 2), the relationship established by equation 9 is obeyed.

$$sen\phi = \frac{y}{r} \rightarrow y = rsen\phi$$

Equation 9

Finally, combining equation 8 and equation 9 yields equation 10, which may be written as equation 11 if it is taken into account that r_o must remain constant to assure the uniformity of the glaze distribution.

$$r(y,\phi) = \frac{r_o(y)\phi}{sen\phi}$$

Equation 10

$$\frac{r}{r_o} = \frac{\phi}{sen\phi}$$

Equation 11

If r_m is defined as the radius of a given circular bell, it may be verified that, when r is equal to r_m, the angle ϕ is equal to $\frac{\pi}{2}$, so that the relationship existing between r_m and r_o can be directly obtained from equation 11, which is:

$$\frac{r_m}{r_o} = \frac{\pi}{2}$$

Equation 12

Equation 11, combined with equation 12, indicates, once r_m or r_o has been defined, what the variation of the curvature radius with the angle ϕ is that the bell must exhibit for the resulting curtain to provide a uniform glaze distribution across the entire width of the tile.

In order better to understand the meaning of these equations, Figure 3 shows the plot, in qualitative form in a red line, of the circular curtain of glaze produced by a conventional bell of radius r. The blue curve corresponds to a curtain that would produce a uniform glaze distribution on the tile, in which r_m would be equal to the radius of the circular bell represented by the red line. Finally, the curve of the green line is another, improved curtain of glaze in which r_o would have the same value as the radius of the circular bell.

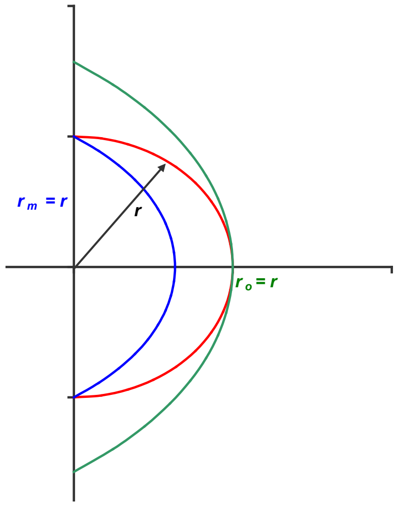

Figure 3. Curtain produced by a conventional circular bell (red line) and the curtain produced by two bells with a uniform distribution (green and blue lines).

As may be verified, it is possible to obtain a bell with a uniform distribution from a conventional circular bell by trimming the edge of the bell. That is, in the case shown in the example of Figure 3, the curve of the blue line could be obtained from a circular bell like the one represented by the red line.

3.3. Simulation of the performance of the improved bell design

With a view to determining whether the proposed design would, in practice, provide the desired advantages, the theoretical performance of a bell such as the one represented by the red line in Figure 3 was compared with that of an improved bell such as the one represented by the blue line.

By developing the equations set out above, it can be shown that the quantity of glaze applied by a bell of revolution with an arbitrary profile is given by equation 13:

$$\frac{m_p}{m_\varphi} = \frac{1}{r\cos\varphi + r'\sin\varphi}$$

Equation 13

where m_p is the quantity of material applied per unit perpendicular length to tile advance (kg/(m s)). If the bell is circular, its radius, r, is constant and its derivative, r′, is cancelled, so that equation 13 becomes equation 14, which allows the total quantity of glaze per unit length applied by a conventional bell of radius r to be calculated.

$$\frac{m_p}{m_\varphi} = \frac{1}{r\cos\varphi}$$

Equation 14

For a bell of uniform distribution like the one proposed, substituting equation 11 in equation 13 yields the expression represented by equation 15.

$$\frac{m_p}{m_\varphi} = \frac{1}{r_o}$$

Equation 15

Equations 13 and 14 show that, for an optimised bell, m_p is constant across the entire tile width, whereas for a conventional bell, this parameter depends on the angle φ and, hence, on the width of the glazed tile.

By way of example, the variation of the average flow rate per unit transverse length for five hypothetical tiles, 20, 40, 60, 80, and 100 cm wide (parameter 2 and according to Figure 2), glazed using a conventional bell with a radius of 50 cm and an optimised bell with a maximum radius of 50 cm, for a glaze mass flow rate per unit angle of 0.15 kg/(s rad), has been calculated

2y (cm)	ϕ (º)	$\bar{m}_p$ (g/(s cm))
20	24	3,02
40	48	3,09
60	74	3,22
80	108	3,48
100	180	4,71

Table 1. Theoretical variation of the average mass flow rate per tile transverse unit applied by a conventional bell.

Table 1 shows that, for a conventional bell, the value of the average mass flow rate per tile transverse unit increases considerably when wider tiles are glazed. This causes the useful area of the curtain of glaze to be practically reduced by 50%, if it is sought to avoid the appearance of defects relating to non-uniform glaze distribution on the tile surface.

2y (cm)	ϕ (º)	$\bar{m}_p$ (g/(s cm))
20	36	4,71
40	72	4,71
60	108	4,71
80	144	4,71
100	180	4,71

Table 2. Theoretical variation of the average mass flow rate per tile transverse unit applied by an optimised bell.

In contrast, as Table 2 shows, the average mass flow rate per unit tile transverse length does not depend on the tile width when an improved bell is used. This assures that a uniform quantity of glaze is applied across the entire tile width, if the bell is correctly balanced, while the useful area of the resulting curtain of glaze is much larger than that of a conventional bell.

The advantages provided by the improved bell stem from the fact that the relationship between tile width and the curtain angle depositing glaze on this area of the tile are independent of the position considered. Indeed, based on the values of the angle of the curtain of glaze deposited on each tile (φ) of Table 1 and Table 2, for a tile 1 m wide, it may be verified that, in the case of the conventional bell, the centre 10 cm are encompassed by a curtain angle of 12º, whereas the 10 cm next to the tile edge are decorated by a curtain angle of 36º. In contrast, for the improved bell, the 10 cm next to the tile centre and the 10 cm next to the tile edge are both decorated by a curtain angle of 18º.

4. MATERIALS AND METHODOLOGY

Starting with a conventional bell, 66 cm in diameter, an improved bell with a maximum radius of 33 cm was obtained by machining the discharge edge of the conventional bell. This was done by transferring the data corresponding to the characteristic curve of the improved edge to the numerical control of a thread electro-erosion machining unit. The excess material was removed and the bell shown in Figure 4 was obtained.

In order to validate the operation of the improved bell, this was set in a pilot glazing line together with a conventional glazing bell with the same dimensions as the original bell from which the improved bell had been obtained. Both bells were fed by a single impeller pump with the same glaze suspension from a tank located next to the line. The work was performed using a glaze suspension of the type customarily used for the decoration of porcelain tile bodies.

The tests for evaluating the distribution of the quantity of glaze applied by both devices consisted of making a metal plate, 40 cm wide and 30 cm long, on which five uniformly distributed metal strips of 5x30 cm were arranged, pass through the curtain created by each bell waterfall, strip number three being located exactly in the centre (see Figure 4). Measuring the mass of glaze deposited on each metal plate enabled the glaze distribution produced by the two devices to be determined under the tested experimental conditions.

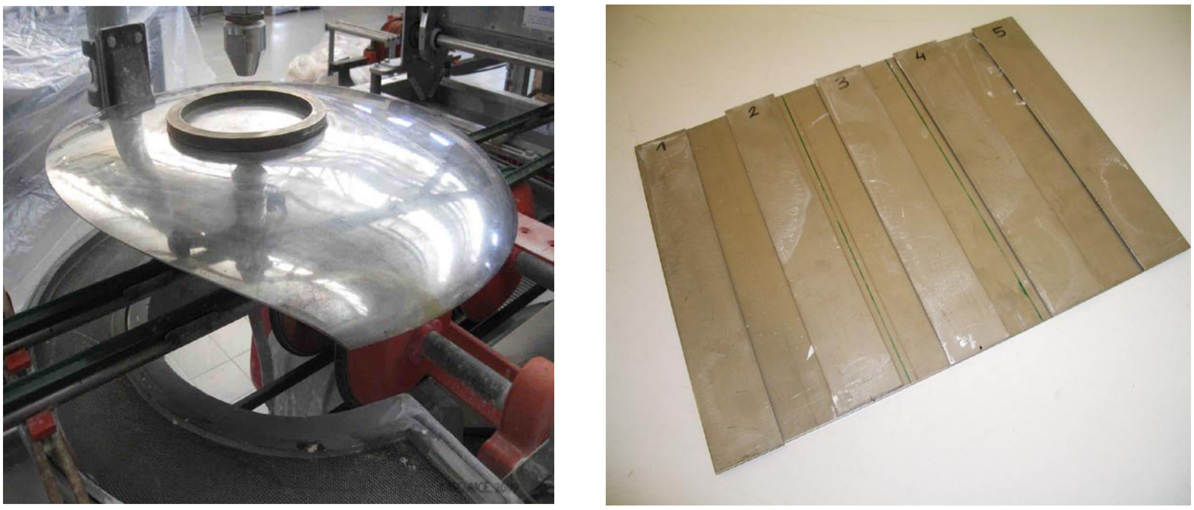

Figure 4. Bell with uniform distribution of the applied quantity of glaze obtained by machining a conventional bell (left), and metal control plate (right).

5. EXPERIMENTAL VALIDATION

Figure 4 shows the two bell waterfalls dropping glaze during the experimental validation of the improved device. The glaze distributions obtained by the experimental procedure described in section 3 are detailed in Tables 3 and 4, in which G_{total} is the quantity of glaze poured on to the entire control plate and Gi the quantity of glaze deposited on each strip. The test was repeated five times with each device in order to obtain an average value of the distribution.

It may be observed that, as was to be expected, the conventional bell displayed a much more heterogeneous distribution of the applied glaze than the optimised bell. In effect, while the conventional bell exhibited a maximum deviation of 3.9 g between the quantity of glaze deposited on the different plates, this difference was only 0.5 g with the improved bell.

Figure 5. Conventional and improved bell during the experimental validation.

The normalised average distributions of the quantity of glaze applied by each device in the tests conducted are depicted in Figure 6. The graph shows that the conventional bell applied a greater quantity of glaze on the tile sides, whereas the optimised bell applied a very similar quantity, which was close to 20% of the total applied glaze, across the entire tile width. Although there were slight departures from the theoretical value of 20%, these differences were always within the experimental error that existed in the measurement of the quantity of glaze deposited on each plate, as shown in the error bars of the graph.

The slight asymmetry observed in the glaze distribution applied by the conventional bell may have been due to a deficient balance of the device while the measurements were being made. This observation demonstrates the great importance of good balance in order to achieve a proper glaze distribution in both a conventional system and in the proposed system.

Measurement	G_{total} (g)	G_{total} (g/cm²)	G_1 (g)	G_2 (g)	G_3 (g)	G_4 (g)	G_5 (g)	ΔG_{max} (g)
1	129,1	0,108	17,3	15,3	15,5	16,4	18,5	3,2
2	128,6	0,107	17,6	15,3	15,1	16,2	18,3	3,2
3	128,6	0,107	17,1	15,7	15,2	16,2	18,2	3,0
4	127,3	0,106	17,0	15,4	14,8	16,0	18,0	3,2
5	124,9	0,104	16,9	14,7	13,9	15,2	17,8	3,9
Average	128,3	0,107	17,1	15,3	14,9	16,0	18,2	3,3

Table 3.Glaze distribution applied by a conventional bell.

Measurement	G_{total} (g)	G_{total} (g/cm²)	G_1 (g)	G_2 (g)	G_3 (g)	G_4 (g)	G_5 (g)	ΔG_{max} (g)
1	99,0	0,083	12,1	12,3	12,3	11,8	12,0	0,5
2	98,8	0,082	12,1	12,3	12,3	11,9	12,1	0,4
3	98,7	0,082	12,1	12,3	12,3	11,9	12,1	0,4
4	100,7	0,084	11,8	12,2	12,3	12,0	12,0	0,5
5	100,4	0,084	11,9	12,2	12,3	12,0	11,8	0,5
Average	99,5	0,083	12,0	12,3	12,3	11,9	12,0	0,5

Table 4. Glaze distribution applied by the improved bell.

The results obtained in the experiments conducted validate the operation of the bell with the improved discharge edge and verify the theoretical equations obtained in section 3. While verification of the satisfactory operation of the device under industrial conditions remains pending, it may be stated that the new bell design assures a much more uniform glaze distribution than that provided by the conventional bell.

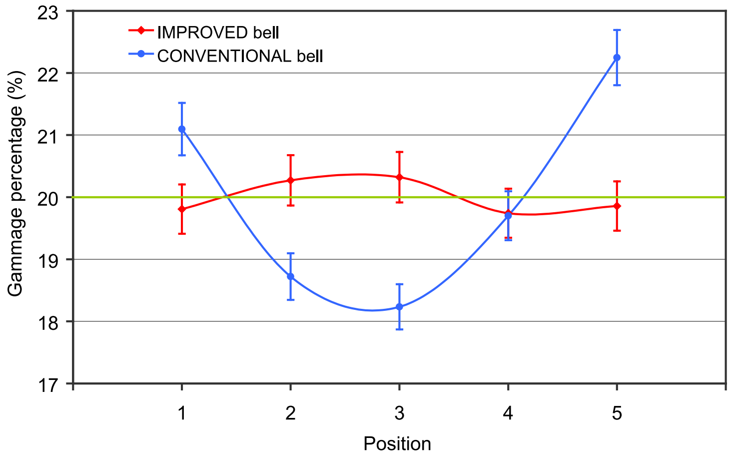

Figure 6. Normalised average distributions of the glaze applied by the two tested devices.

6. CONCLUSIONS

The following conclusions may be drawn from the present study:

- The geometry of the glaze deposition process in the form of a semi-circular curtain of glaze on the ceramic tiles was studied and it was verified that the differences in the quantity of glaze applied between the edges and the centre of the tile occurred because the arc of the curtain per unit tile transverse length was greater at the sides than in the centre of the tile.
- A representative equation of the discharge edge curvature of a glazing bell was deduced that keeps the angle of the curtain of glaze deposited per unit tile transverse length constant across the entire width of the decorated tile.
- A bell waterfall was constructed whose discharge edge had the curvature represented by the deduced equation and its operation was validated under actual operating conditions.

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