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Prevention of Explosive Atmospheres Through the Controlled Application of Flammable Products on Surfaces

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Abstract

In architecture and construction, it is common to use acrylic products with a high flammable content, from lacquers to improve the curing of concrete and mortar to resins that offer protection, sealing, flexibility and elasticity properties. The drying process of the treated surface involves the formation of volatile organic compound (VOC) vapours. To prevent these from degenerating into a potentially dangerous flammable atmosphere, a procedure is presented that establishes the maximum application yield for solvent-based products, providing equations that relate the maximum application surface area and minimum drying time to the air velocity available in the work area. The results are provided for both indoor and outdoor applications. A maximum application speed is established to prevent the generation of areas classified as fire or explosion hazards: 1.5 m²/h indoors and 1 m²/h outdoors. When this is carried out at an ambient temperature of 20 °C, and above 40 °C, it is not possible to apply varnishes without generating a flammable atmosphere.

Keywords: hazard control; volatile organic compounds (VOCs); explosive atmospheres (ATEX); application of lacquers; varnishes and solvents

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1. Introduction

Architecture designs buildings intended to stand the test of time through the application of adhesives and protective coatings [1], such as natural lacquer, which has been used by humans since the Neolithic period [2,3]. On the other hand, techniques aimed at reducing environmental impact and improving both the durability and performance of cements and concretes are constantly evolving [4], with the curing process being fundamental in determining the mechanical performance, durability and sustainability of structures [5], including high-strength concretes [6] and precast elements [7].

In hot environments, it is common to use lacquers that slow down water evaporation during the curing process of concrete and mortar. Commercial acrylic lacquer preparations usually have a solvent content of over 50.0%, generally xylene and ethylbenzene, which means that the product used in applications has flash points of around 20 °C. In addition, varnishes are commonly used for priming and consolidation. In these, the solvent is the main component of the mixture.

Both the application of lacquers and the curing process of concrete often involve the use of volatile organic compounds (VOCs) [8,9], which entail risks such as combustion due to the accumulation of their vapours, due to poor ventilation [10]. Within the framework of advances in the development of models for safety in the field of risk management [11–14], methods are available that allow the characterisation of the combustion and explosion of vapours from flammable organic liquids and mixtures used in surface coatings [15–21], developing techniques that reduce their hazardousness, such as the addition of flame retardants [22].

The drying capacity of building materials, influenced by surface air flow and the size of the treated surface, has been studied [22], as has the evaporation process of (VOCs) [23–25]. However, the models consider air speeds higher than those typically found in work environments, and tend to overestimate the influence of air speed and underestimate the influence of the length of the evaporation surface [26]. The application of a thin film can cause brief but highly concentrated emissions, as small spills reach maximum evaporation immediately after they occur [27,28], with aqueous mixtures of hydrophobic compounds having a particular impact [26].

This study examines how to determine the limits of application to prevent the formation of a dangerous explosive atmosphere, taking international standards [29,30] as a reference, considering the maximum application area and the necessary waiting time between applications, thereby establishing the maximum working performance, taking into account the vapour retention time after application of the products.

2. Materials and Methods

Commercial acrylic lacquer preparations usually have a solvent content of over 50.0%, generally xylene and ethylbenzene, which means that the product used in applications has flash points of around 20 °C. In addition, it is common to use varnishes for priming and consolidation, in which the di-solvent is the majority compound in the mixture. Consequently, the application of both lacquers and the strippers used to remove them leads to the formation of a continuous film of flammable products, which during the drying process can result in the creation of a hazardous location due to the risk of fire and explosion.

The aim is to establish the maximum application area for both commercial acrylic lacquers and varnishes so that the vapours generated do not pose a risk. If an explosion were to occur, the consequences would be negligible, the pressure wave generated would not cause damage, and the inflammation would not generate enough heat to cause damage or fire to surround materials [29,30].

The extent of the hazardous area is determined by the available ventilation, which has a dual and antagonistic influence: increased air velocity allows the vapour generated during the drying process to be diluted, but at the same time accelerates evaporation from the surface of the liquid [22,26].

A characteristic parameter in ventilation is the number of air changes per unit of time [29,31]:

$$C = \frac{Q_a}{V_0} = \frac{w \cdot A_w}{V_0} = \frac{w \cdot L_0^2}{L_0^3} = \frac{w}{L_0} \tag{1}$$

Where:

C = Number of air changes (s^{-1})
Q_a = Air flow (m^3/s)
V_0 = Total volume to be ventilated (m^3)
w = Air velocity (m/s)
A_w = Cross-sectional area, which cuts through the air (m^2)
L_0 = Length of the air path inside the volume to be ventilated (m)

This mathematical expression allows the air velocity on the surface of the applied product to be obtained. In calculating the evaporation rate of volatile chemicals, velocities between 0 and 5.1 m/s are considered [32].

In the model presented, ventilation has been estimated by applying the international standard IEC 202007IN, which considers an air velocity for small environments in poorly ventilated spaces of 35.0 air changes per hour. This determines that the air changes per hour are 0.01 s^{-1}, which implies an air velocity of 0.05 m/s. In open environments, the speed is 0.5 m/s, i.e., ten times higher, so the value of C will be 0.03 s^{-1}. For its part, the international standard IEC 60079-10-1 considers, for the worst-case scenario with regard to vapour dispersion, a wind speed of 0.25 m/s, just above the ground in calm weather conditions [29–34].

Through the longitudinal section of the route inside the volume to be ventilated, a constant air flow of fifteen metres on the open-air side and 1.7 m on the poorly ventilated interior side is considered [30].

On the other hand, there is also the possibility of using the ventilation systems available in buildings, in which case the maximum flow velocities are less than 6 m/s [32–36] (Table 1):

Table 1. Standardised air velocity [32–34].

Indoor application		Outdoor application	
Small, poorly ventilated environments (m/s)	**Maximum air speed (m/s)**	**IEC 202007:06 (m/s)**	**IEC 60079-10-1:22 (m/s)**
0.05	6	0.5	0.25

Although a constant air flow is considered throughout the longitudinal section of the route inside the volume to be ventilated, its behaviour is not homogeneous, as it presents a gradient that tends towards zero over the structures themselves, which is particularly significant at high air speeds.

It should be noted that the use of conventional air conditioning systems to dry surfaces is not permitted, as flammable vapours are transferred to the installation itself, making it necessary to establish a specific explosive atmosphere (ATEX) marking.

Liquids in equilibrium with the surrounding atmosphere generate a layer of vapour above their surface, which can cause the concentration of this vapour to exceed the lower flammability limit of the substance or mixture and, as a result, create an explosive atmosphere.

The amount of vapour generated depends on the temperature of the liquid and the surrounding air flow. The substance is considered to be in thermodynamic equilibrium with the environment and at the same temperature as the surrounding air. In addition, it is estimated that air circulation in the drying area is less effective in diluting the vapour generated than in the rest of the volume considered.

Scientific literature proposes two equations that allow us to obtain the vapour generated on the surface of an uncooled flammable liquid exposed to the atmosphere [29]:

$$\mathrm{Q_g} = \frac{18.3 \cdot 10^{-3} \cdot \mathrm{u_w^{0.78}} \cdot \mathrm{A} \cdot \mathrm{P_v} \cdot \mathrm{M^{0.667}}}{\mathrm{R} \cdot \mathrm{T}} \qquad (2)$$

Where:

Q_g = Liquid evaporation rate (Kg/s)
U_w = Wind speed at the surface of the liquid (m/s)
A = Evaporation area of the free surface of a liquid (m^2)
P_v = Vapour pressure of the flammable substance (Pa)
M = Molar mass (kg/Kmol)
T = Fluid temperature (°K)
R = Universal gas constant (8314.5 J/kmol ·K)

For liquids with low vapour pressure, which are at a temperature far from their boiling point, the following equation is also available [30]:

$$\mathrm{Q_g} = \mathrm{A} \cdot 2 \cdot 10^{-3} \cdot \frac{\mathrm{u_w}}{\mathrm{f}} \cdot \mathrm{r_{eq}^{-0.11}} \cdot \frac{\mathrm{M} \cdot \mathrm{P_a}}{\mathrm{P_a} - \mathrm{P_v}} \cdot \ln\left(1 + \frac{\mathrm{P_v}}{\mathrm{P_a} - \mathrm{P_v}}\right) \qquad (3)$$

Where:

Q_g = Liquid evaporation rate (Kg/s)
A = Evaporation area of the free surface of a liquid (m^2)
u_w = Wind speed at the surface of the liquid (m/s)
f = Ventilation efficiency factor, values range from 1 to 5 (as this is a process of evaporation from a surface, ventilation efficiency is minimal f = 5) (dimensionless)
R_{eq} = Equivalent radius of the liquid surface (m)

$$\mathrm{r_{eq}} = {}^{(2 \cdot \mathrm{area})}\big/_{(\mathrm{perimeter})} \qquad (4)$$

Where:

M = Molar mass (kg/Kmol)

P_a = Atmospheric pressure (Pa)

P_v = Vapour pressure of the flammable substance (Pa)

The determination of conditions for safe application is based on obtaining a non-hazardous spread zone, which requires high dilution to quickly reduce the vapour concentration on the surface and ensure that it does not remain after the application is complete. These conditions are met with flammable volumes of less than 0.1 m³ [29,31].

To determine this, the vapour is characterised by the following equation [12]:

$$Q_c = \frac{Q_g}{LFL \cdot \rho_g} \tag{5}$$

Where:

Q_c = Characteristic of exhaust, in (m³/s)

Q_g = Liquid evaporation rate (Kg/s)

ρ_g = Vapor density (Kg/m³)

LFL = Lower flammability limit (vol/vol)

To obtain a negligible theoretical extension area, the characteristic evaporation value must be less than 0.001 m³/s [29].

The required drying time between applications is implemented so that the average concentration of vapour in the air falls below its lower flammability limit, the value of which is obtained using the following equation [30]:

$$t = \frac{-f}{C} \cdot \ln \frac{LFL \cdot k}{X_0} \tag{6}$$

Where:

t = Maximum residence time of the generated steam (s)

X_o = Initial concentration of flammable substance expressed in the same units as the LFL, i.e., in % vol or in kg/m³.

C = Number of fresh air changes per unit of time (s^{-1})

f = Factor due to the mixture not being perfect (dimensionless)

k = Safety factor applied to the LFL (typical value k = 0.25) (dimensionless)

The safety factor is applied because the effective ventilation capacity is always lower than the available capacity, and explosive mixtures may exist at temperatures up to 15 °C below the flash point [37].

Finally, the maximum application speed for each product is obtained by calculating the ratio between the maximum application area and the drying time, which has been assimilated to the permanence of the vapour.

$$\frac{t}{3600} = t_h \tag{7}$$

Where:

t = Maximum residence time of the generated steam (s)

t_h = Minimum drying time (h)

The application parameters, maximum surface area and drying time for the solvent toluene in confined environments and poorly ventilated spaces are as follows (Table 2).

Table 2. Application parameters of toluene in poorly ventilated environments.

Model	Characteristic value of the escape Q_c (m³/s)	Maximum application surface (m²)	Minimum drying time (h)
IEC 202007:06	$8.02 \cdot 10^{-4} \cdot A$	1.24	0.80
IEC 60079-10-1:22	$6.44 \cdot 10^{-4} \cdot A$	1.50	

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The maximum working pace that allows a safe environment to be maintained during the application of the solvent toluene is:

$$\mathrm{V_{aplication}} = \frac{\mathrm{A}}{\mathrm{t_h}} \tag{8}$$

Where:
V = Performance: Maximum application speed (m^2/h)
A = Maximum application area (m^2)
t_h = Minimum drying time (h)
LFL = Lower flammability limit (vol/vol)
The maximum yield for manual application of toluene is:

$$V_{aplication} = \frac{1.24}{0.80} = 1.55 \ {m^2}/{h}$$

The results obtained using the proposed calculation method are associated with environmental conditions of 20 °C and atmospheric pressure. The drying of products will not always occur under these conditions, so different mathematical models have been developed to obtain results based on the drying temperature. The best known is Antoine's equation [38]:

$$\log_{10}(\mathrm{P_v}) = \mathrm{A} - \left[\frac{\mathrm{B}}{\mathrm{T + C}}\right] \tag{9}$$

Where:
P_v = Vapour pressure (mmHg)
T = Temperature (°C)
A, B, C = Antoine coefficients (dimensionless)
The maximum surface area to which it can be applied without creating a risk decreases as the air velocity increases due to an increase in the amount of vapour passing into the atmosphere, with the decrease being more pronounced at lower air velocities, according to the following equation:

$$\mathrm{A} = \frac{6.16 \cdot 10^{-2}}{\mathrm{w}} \tag{10}$$

Where:
A = Maximum area of application (m^2)
w = Air velocity (m/s)
The time that must be observed between applications follows the same pattern of behaviour:

$$\mathrm{t_h} = \frac{\mathrm{a}}{\mathrm{w}} \tag{11}$$

Where:
t_h = Minimum drying time (h)
w = Air velocity (m/s)
a = Characteristic parameter of the location (dimensionless)
Indoor environments: **a** = 0.0409
Indoor environments **a** = 0.1228

3. Results

Toluene has a greater capacity to generate a potentially dangerous flammable atmosphere than acrylic lacquers and varnishes, so its application results in lower work yields. The results obtained for the characteristic air velocities in each zone, in accordance with international standards IEC 202007IN and IEC 60079-10-1 [29,30], are shown below (Table 3).

As the air speed increases, the surface dries more quickly, significantly reducing the time required to wait before continuing with the application of the products. However, this increase in air flow over the drying surface increases the amount of flammable vapour released into the atmosphere, which also reduces the application area.

Table 3. Application parameters for toluene at 20 °C and atmospheric pressure, taking into account standardised air velocities [29,30].

		Air velocity (m/s)		
		Indoor	**Outdoor**	
		0.05	**0.5**	**0.25**
Maximum application area (m^2)	**IEC 202007IN**	1.23	0.12	0.24
	IEC 60079-10-1	1.5	0.25	0.44
Minimum drying time (min)	**IEC 202007IN**	49.0	14.4	29.5
Application speed (m^2/h)	**IEC 60079-10-1**	1.9	1.0	0.9
	IEC 202007IN	1.5	0.5	0.5

The application speed required for the work to be considered safe differs depending on the equation used, with the value obtained indoors at high air speeds being particularly significant, with the international standard IEC 202007IN [30] offering more restrictive values.

The amount of flammable vapour increases with temperature, causing a drastic decrease in the application speed of the product to avoid the generation of a flammable atmosphere (Table 4).

Table 4. Application parameters for toluene at 40 °C and atmospheric pressure, taking into account standardised air velocities [29,30].

		Air velocity (m/s)		
		Interior	**Exterior**	
		0.05	**0.5**	**0.25**
Maximum application area (m^2)	**IEC 202007IN**	0.31	0.03	0.06
	IEC 60079-10-1	0.43	0.07	0.12
Minimum drying time (min)	**IEC 202007IN**	48.6	14.4	29.4
Application speed (m^2/h)	**IEC 60079-10-1**	0.53	0.29	0.27
	IEC 202007IN	0.38	0.13	0.13

To obtain a negligible theoretical extension area, the characteristic value of the escape must be less than 0.001 m3/s [29], so for the solvent toluene, the maximum application surface area for confined environments in poorly ventilated spaces is as follows (Table 5).

Table 5. Standardised air velocity [32–34].

Model	**Evaporation rate Q_c (m^3/s)**	**Maximum application area (m^2)**	**Minimum drying time (min.)**
IEC 202007:06	$8.02 \cdot 10^{-4} \cdot A$	1.24	48
IEC 60079-10-1:22	$6.44 \cdot 10^{-4} \cdot A$	1.5	

To analyse the difference in behaviour between the values obtained by applying both standards, the deviation in the maximum application surface area of toluene is studied under ambient conditions of 20 °C and an atmosphere of pressure as a function of air velocity (Figures 1 and 2).

The results obtained by applying standards IEC 202007IN and IEC 60079-10-1 show similar behaviour at high air speeds, while as ventilation decreases, the differences increase, with standard IEC 202007IN offering more conservative values.

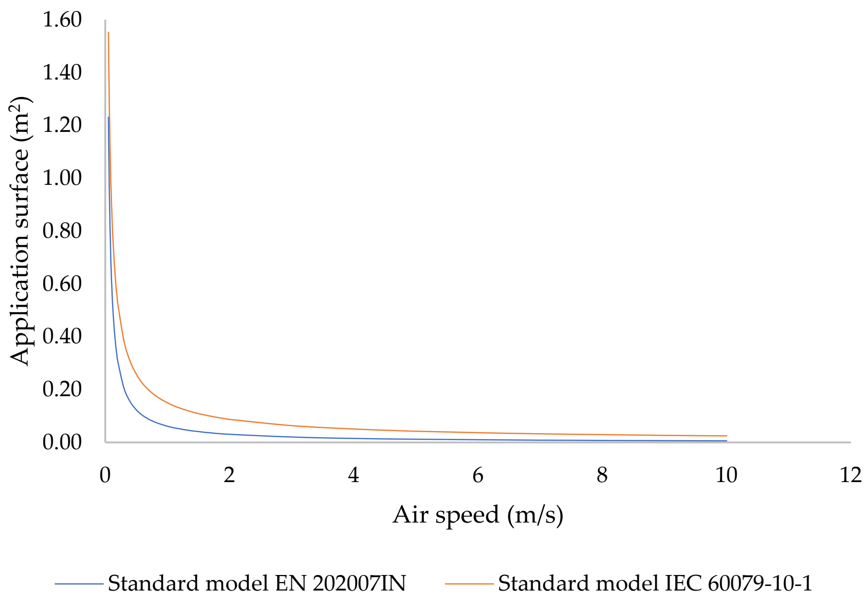

Figure 1. Maximum indoor application area of toluene depending on air velocity.

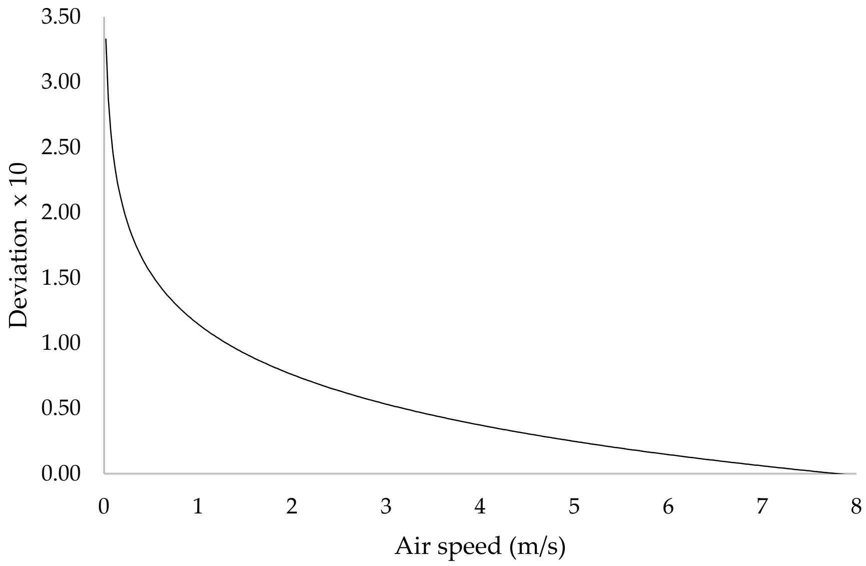

Figure 2. Deviation in the maximum indoor application surface values for toluene as a function of air velocity, with respect to the international standard used.

The analysis of the behaviour of the product application parameters, depending on the ambient temperature, is carried out by studying commercial toluene. This has a purity of over 99.0%, so Antoine's equation can be applied to obtain values for the vapour saturation pressure as a function of temperature. For this situation, the application limits in this case are between 6 and 136 °C.

$$log_{10}(P_v) = 6.95464 - \left[\frac{1344.8}{T + 219.482}\right] \tag{12}$$

The calculation process used is only valid for drying the product. Consequently, the temperature at which this occurs must always be lower than the boiling point of the substance in question, which in the case of toluene is 111 °C.

The values obtained have been obtained considering the ventilation conditions established in the IEC 20007IN standard for poorly ventilated interiors (Figures 3 and 4).

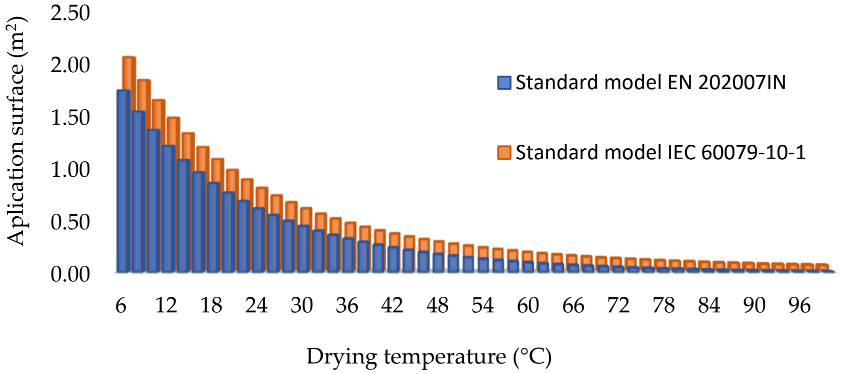

Figure 3. Maximum application area for toluene in poorly ventilated interiors depending on the drying temperature.

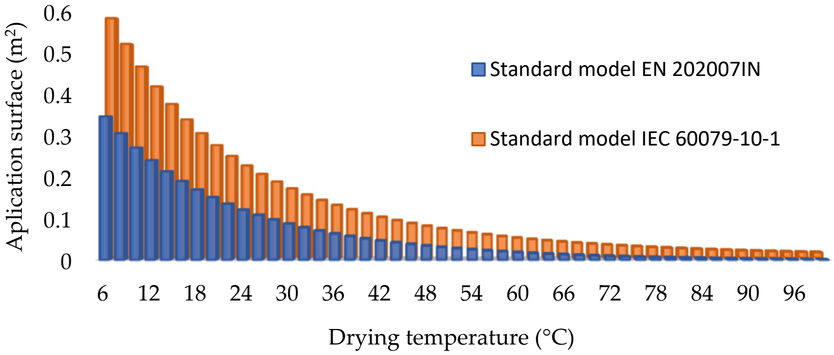

Figure 4. Maximum application area for toluene in outdoor areas depending on drying temperature.

The values provided have been obtained by considering the outdoor ventilation conditions established in standard IEC 20007IN and the air velocity proposed in IEC 60079-10-1, as this better match the expected air flow over a drying surface.

The influence of temperature on the application surface again shows similar behaviour to that offered with regard to ventilation. The values obtained by applying the IEC 20007IN standard are always lower, with the difference becoming more pronounced as the temperature decreases.

Outdoors, where air velocity is higher, the difference in behaviour between the values obtained by both standards is more pronounced.

It should be noted that the vapour pressures obtained by applying Antoine's equation are higher than the actual values published in standard IEC 20007IN, 1830 Pa at 20 °C and 6650 Pa at 40 °C, while those calculated are 2911. 31 Pa at 20 °C and 7886.94 Pa at 40 °C Pa, which represents a deviation from the ideal behaviour of 59.0 and 18.6% respectively. This implies that the higher the temperature, the lower the deviation.

Of the compounds analysed, the solvent toluene has the greatest capacity to generate a potentially dangerous flammable atmosphere, so its application leads to lower work performance.

The results obtained for a commercial solvent-based acrylic lacquer are shown below. The influence of air velocity on the maximum application surface, both indoors and outdoors, is as follows (Figure 5):

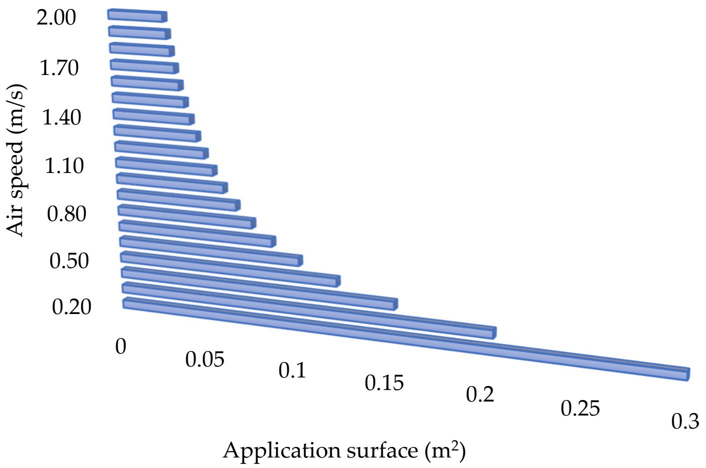

Figure 5. Superficie máxima de aplicación de laca acrílica comercial.

The influence of air velocity on the minimum drying time for a solvent-based acrylic lacquer is as follows (Figures 6 and 7):

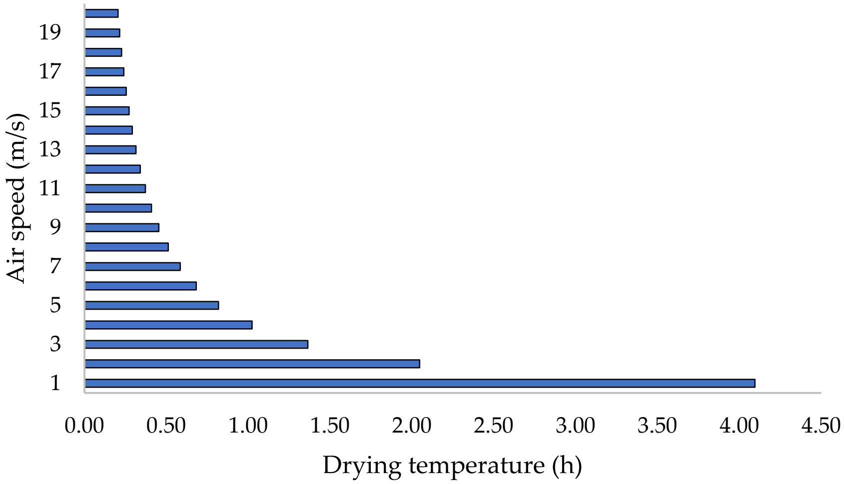

Figure 6. Minimum interior drying time for a commercial acrylic resin.

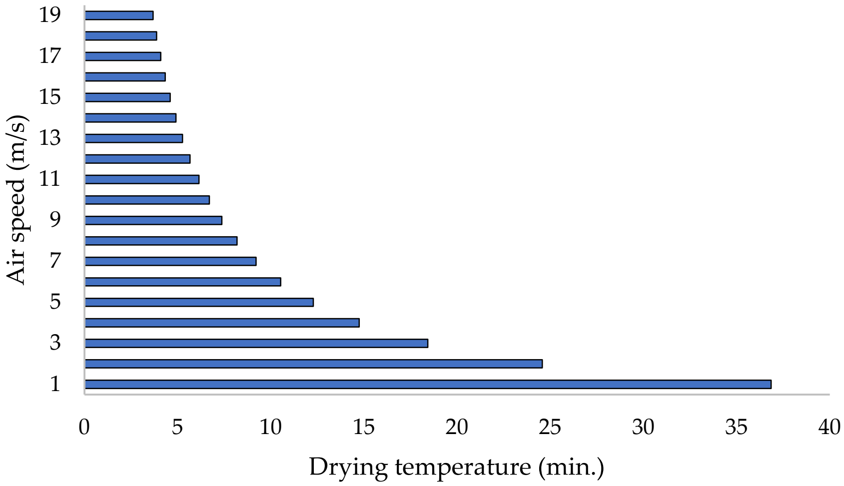

Figure 7. Minimum outdoor drying time for a commercial acrylic resin.

4. Discussion

The increase in surface air flow velocity allows for greater dilution of the vapours generated during the drying process. As a result, the waiting times between applications increase, but at the same time the vapour flow rate generated also increases, which causes the maximum application surfaces to decrease, so that yields remain constant.

Indoors, the standards used define a calculation volume that is much lower than that considered for outdoor environments. Consequently, the results obtained by applying the international standard IEC 20007IN are more appropriate, as it considers ventilation efficiency as a factor. For outdoor use, the latest published version of the standards for calculating explosive atmospheres should be used, i.e., the international standard IEC 60079-10-1.

Forced ventilation of the building to dry surfaces cannot be considered, since, even if no hazardous area is generated in the work area, the evaporation rate is very high and the flammable vapours are transferred to the installation itself, which must therefore have the specific ATEX marking.

Finally, it should be noted that the use of Antoine's equation to determine the evaporation rate as a function of ambient temperature is only applicable to pure substances subjected to high temperatures.

5. Conclusions

Calculation procedures have been studied to obtain maximum application yields for solvent-based acrylic lacquers, varnishes and solvents themselves, so that a potentially dangerous flammable atmosphere is not generated on concrete and mortar pavements, allowing these times to be incorporated into project planning and structuring.

Indoors, solvents evaporate more slowly, as they do at low temperatures, allowing for higher application speeds without creating a potentially dangerous flammable atmosphere.

To avoid the creation of areas classified as fire or explosion hazards, a maximum application speed of 1.5 m^2/h indoors and 1 m^2/h outdoors is established when the ambient temperature is 20 °C.

As the ambient temperature increases, the application speed must decrease, and at around 40 °C it is not possible to apply varnishes without creating a flammable atmosphere.

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administration. A.R.-S.: visualization, supervision, data curation, validation, and resources. B.M.V.-E.: visualization, supervision, methodology, formal analysis, and resources. All authors have read and agreed to the published version of the manuscript.

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Abbreviations

The following abbreviations are used in this manuscript:

ATEX	Explosive Atmospheres
IEC	International Electrotechnical Commission
VOCs	Volatile Organic Compounds

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