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Thermal characterization of the end-forming process of PVC pipes: influence of the number of lamps on critical angular velocities

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Abstract

The end-forming, or belling, of plastic pipes allows them to be joined together to form longer ducts. The first stage of the process entails softening the pipe wall through heating, and defines the properties of the final product. Because of the very low value of thermal conductivity of plastics and to speed heating up, the pipes are placed in ovens whose walls are lined with infra-red short-wave (SW) lamps. The radiation emitted partly penetrates the pipe wall, quickening the process. The heating elements have a straight configuration, and can only be laid axially flush over the oven's wall, the pipes, therefore, must rotate to obtain a circumferentially uniform heating and avoid damage. The threshold speed to avoid scorching while exceeding a desired temperature over the thickness of the pipe wall is defined as "critical angular velocity" and is strictly dependent on pipe geometry and oven characteristics such as the number and layout of lamps. The Authors have already investigated the problem extensively, as is well documented in the literature, yet one aspect still remains to be studied, namely the influence of the number of lamps on the heat flux distribution over the pipe's perimeter and on the critical velocity. In this work, the issue is investigated thoroughly using the same approach previously adopted and recalled in its main aspects in the paper. It is found that even a significant reduction in the number of lamps does not increase threshold velocities to technically unfeasible values. A non-negligible reduction in costs can therefore be achieved without significant impact on the process outcomes.

Keywords: Radiation heat transfer; end-forming ;

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1. Introduction

Plastic pipes have a wide field of application, and are extensively employed in constructions to convey water and other fluids [1] for e.g. disposing of wastewater or circulating warm water for heating purposes [2].

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In order to create longer ducts, pipes need to be joined together, which can be accomplished by enlarging one of their ends [3]. The process is called belling or end-forming, and it has been less studied than industrial techniques like Injection Stretch Blowing Moulding (ISBM), where PVC pre-forms are heated in order to soften the polymer and make it amenable to mechanical deformation [4, 5]. Heating is accomplished in many cases by means of expensive plane short-wave infra-red lamps. Since heating does not occur uniformly due to the geometry of the heaters, the pipe must be kept in rotation with an angular velocity which allows a circumferential temperature distribution close to uniform. Also, temperature across the pipe thickness must be controlled so that the material is softened enough for deformation but does not burn or deteriorates [6]. The Authors have already investigated several issues related to the heating step of the process: in [7] the problem was first tackled by determining the dynamic view factors between the lamps and the rotating cylinder, the influence of the angular velocity on the temperature distribution over the pipe thickness was determined and the boundary conditions in terms of convective heat transfer coefficients and internal heating were investigated. The results were used in[8] to determine the critical values of the angular velocity and the layout of the lamps was studied, whilst in [9] the heating cycle subject to a surface temperature control was investigated. The latter study highlighted how certain operating conditions may lead to thermal damage, especially for low angular velocities and high convective coefficients because the maximum temperature is reached within the pipe wall rather than at its surface. This paper analyses an aspect which had not been given attention so far, namely the influence of the number of lamps on the end-forming process and the determination of the critical angular velocities needed to keep temperature over the entire pipe wall within the bonds desired.

Nomenclature

$\overline{a}$	Ratio between pipe external radius and lamp radial position $(-)$
c	Specific heat capacity of PVC $(J \cdot kg^{-1} \cdot K^{-1})$
$F_{i\rightarrow j}$	View factor between finite extension elements $(-)$
g	Control function $(-)$
h	Convection heat transfer coefficient $(W \cdot m^{-2} \cdot K^{-1})$
i	Finite extension lamp
I	Heat flux $(W \cdot m^{-2})$
j	Finite extension arc on cylinder outer circumference
k	Thermal conductivity of PVC $(W \cdot m^{-1} \cdot K^{-1})$
K_a	Absorbtion coefficient of PVC (m^{-1})
L_h	Lamps heating length (mm)
L_t	Lamps total length (mm)
N	Number of finite extension arcs along pipe outer circumference $(-)$
P_r	Lamps rated power (W)
q_g'''	Heat generation term $(W \cdot m^{-3})$
r	Generic radial coordinate (mm)
re	Pipe external radius (mm)
ri	Pipe inner radius (mm)
rm	Pipe mean radius (mm)
R_L	Lamps radial position (mm)
T	Temperature (K)
T_{burn}	Burnout temperature for PVC (K)
T_{heat}	Heating temperature for PVC (K)
T_{min}	Lamp switching on temperature (K)
T_{max}	Lamp switching off temperature (K)
T_s	Softening temperature of PVC (K)
th	Pipe thickness (mm)

x	Generic coordinate along lamp extension (mm)
$\overline{x}$	Non-dimensional coordinate along lamp extension ($-$)
$\overline{x}_1$	Non-dimensional coordinate $\overline{x}$ calculated at the first end of the lamp ($-$)
$\overline{x}_2$	Non-dimensional coordinate $\overline{x}$ calculated at the second end of the lamp ($-$)
α	Thermal diffusivity of PVC ($m^2 \cdot s^{-1}$)
α_L	Lamp angular position (deg)
$\Delta\theta$	Angular extension of finite arcs on pipe outer circumference (rad)
ΔT	Maximum temperature displacement with respect to the case of a uniform radiation (K)
ΔT_{eval}	Representative temperature displacement to be compared with ΔT_{max} (K)
ΔT_{max}	Maximum allowable temperature displacement (K)
ε	Emissivity of PVC ($-$)
θ	Angular position along pipe outer circumference (rad)
$\theta_{control}$	Angle between the normal to cylinder outer surface at a point M and the line joining M to a generic point P on the i-th lamp (rad)
ρ	Density of PVC ($kg \cdot m^{-3}$)
σ	Stefan-Boltzmann constant ($W \cdot m^{-2} \cdot K^{-4}$)
τ	Time (s)
τ_b	Burnout time (s)
τ_h	Heating time (s)
ω	Pipe angular velocity ($rad \cdot s^{-1}$)

2. End-forming

End-forming, or belling, is a manufacturing process through which the ends of pipes are enlarged so as to allow them to be joined to the butt end of another pipe of the same diameter (which retains its original shape and diameter) in order to form longer pipelines. End-forming occurs through mechanical action of an expandable spindle, over which the pipe is placed after its end has been heated so as to soften the material. The clamps of the spindle are then opened, widening the pipe diameter in that zone, and the pipe is held in place onto the spindle either by mechanical action or with the use of compressed air. Once the belling has taken place, the pipe is cooled (by air or water mist) and removed for further operations.

2.1. Oven

Heating during end-forming is crucial to ensure that the pipe material reaches a suitable temperature throughout the pipe wall, else deformation becomes impossible (temperature too low) or the material releases some of its constituents (usually chlorine) and can become scorched or even burnt locally, see [3, 6]. There are several techniques which are employed to heat the pipe ends: for PVC pipes one method is to employ short-wave infra-red lamps, whose thermal radiation penetrates the material with a distribution according to Lambert's law for absorbing media. Lamps are chosen to match their emission characteristics to the absorption properties of the materials: for PVC, quartz emitters are chosen, whose emissivity is uniform in the wavelength spectrum of interest [10]. The luminary is rectangular in shape, which justifies the assumption of planar source. Another characteristic of the oven, see Fig.1(a), is the vents which allow ambient air to be circulated over the surface of the pipe to avoid scorching, in a way similar to air-cooled heat sinks, [11]. For pipes of larger size, the oven is also equipped with lamps that heat the inner side of the pipe to speed up the process and prevent uneven temperature distribution or peaks. The pipe is rotated continuously during the heating phase, in order for the planar heaters to recreate conditions close to those of uniform heat flux: the minimum velocity which allows to approximate this condition is called ”critical angular velocity”.

In this work the influence of the number of outer lamps on the critical velocity for pipes of three different outer radii, R_e, namely 62.5, 90 and 125 mm is investigated, starting from the customary arrangement of

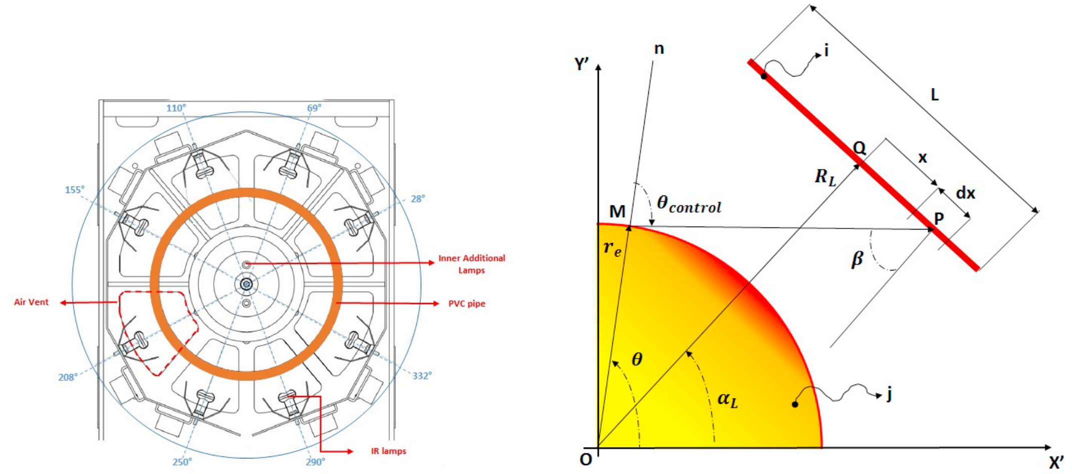

Fig. 1. (a) Section of the oven with pipe, 8 lamps; (b) Calculation of the view factor.

eight lamps, equally spaced, down to four. Three lamps are considered for heating the inner of the pipe and flow conditions are fixed, with heat transfer coefficients calculated through correlations presented in [12] and [13] and equal to $h_i = 4\,W \cdot m^{-2} \cdot K^{-1}$ for the inner side and $h_e = 18\,W \cdot m^{-2} \cdot K^{-1}$ for the outer. The influence of the heat transfer coefficient on the process has been previously analysed in [7].

2.2. Material

Pipes undergoing belling can be of several materials; in this study, the analysis concerns the most common type, i.e. polyvinyl chloride (PVC). Thermophysical properties for this case are: density $\rho = 1.44\ g \cdot cm^{-3}$, thermal conductivity $k = 0.18\ W \cdot m^{-1} \cdot K^{-1}$, specific thermal capacity $c = 1005\ J \cdot kg^{-1} \cdot K^{-1}$, softening temperature $T_s = 80°C$, surface emissivity $\varepsilon = 0.93$ and absorbtion coefficient for infrared radiation $K_a = 147\ m^{-1}$, which directly affects the quantity of energy absorbed by the material when considering a certain kind of emitter. The value of K_a has been established on the basis of information from lamp manufacturers working in this field. Particular attention must be paid to the maximum temperature reached to avoid decomposition phenomena such as a dehydrochlorination process, which consists of hydrogen chloride production and, for commercial PVC, often starts at temperatures in the range 520-590 K, [14]. Moreover, when reaching a temperature level of about 450 K, scorches and surface whitening phenomena begin to appear, making the product unacceptable.

3. Model

Two different models have been devised to study the influence of the number of lamps on the process. One describes the radiative heating of a static polymeric tube, the other the radiative heating of a rotating pipe considering the instantaneous angular distribution of the radiation over the tube. The former model can be seen as an asymptotic form of the latter (e.g. $\omega \longrightarrow +\infty$). Both models are bi-dimensional, as the distribution of temperature along the pipe axis can be considered uniform over the heated length [7]. Whilst for the model with uniform radiation it is enough to calculate a global view factor between lamps and pipe on the basis of correlation available in literature, [15], in order to simulate the radiative heat exchange between a rotating pipe and the lamps, the angular distribution of the view factors as a function of tube outer radius and oven configuration must be determined, as detailed in [7] and [8].

3.1. View Factor

In the following, the main steps described in [7] will be reported.
The portion of energy leaving an infinitesimal element on the external surface of the cylinder j at an angular position ϑ which reaches an infinitesimal element of extension dx on a generic lamp i is:

$$dF_{dj\to di} = \frac{1}{2}\cdot d(sin(\vartheta_{control})) \tag{1}$$

Referring to Fig.1(b), $\vartheta_{control}$ represents the angle between the normal to the outer surface of the pipe on a generic point M and the vector $\overrightarrow{MP}$, where P is a generic point on the surface of the lamp. After introducing the non-dimensional quantities $\overline{x} = x/R_L$ and $\overline{a} = r_e/R_L$, Eq.1 becomes:

$$dF_{dj\to di} = \frac{1}{4}(1+g)\frac{[cos(\vartheta-\alpha_L)-\overline{a}-\overline{x}(1-\overline{a}cos(\vartheta-\alpha_L))sin(\vartheta-\alpha_L)]}{[1+\overline{x}^2+\overline{a}^2+2\overline{a}(\overline{x}sin(\vartheta-\alpha_L)-cos(\vartheta-\alpha_L)]^{\frac{3}{2}}}d\overline{x} \tag{2}$$

In Eq. 2 g represents a control function defined as $g = sign(\overrightarrow{OM}\bullet\overrightarrow{MP})$, which accounts for the portion of cylinder surface in the shadow zone of the i-th lamp. Numerical integration of Eq. 2 between $\overline{x}_1 = -L/2R_L$ and $\overline{x}_2 = +L/2R_L$ leads to $F_{dj\to i}$, which represents the fraction of energy leaving an infinitesimal element on the external pipe surface reaching lamp i of finite extension L. The fraction of energy $F_{i\to dj}$ leaving the i-th lamp of finite extension L which reaches an infinitesimal element of extension $r_e\cdot d\vartheta$ on the outer surface of the cylinder j at an angular position ϑ is obtained by reciprocity:

$$F_{i\to dj} = F_{dj\to i}\frac{r_e\cdot d\vartheta}{L} \tag{3}$$

To have a distribution of the view factors on the outer side of the cylinder, the outer circumference must be discretised into N angular arcs, each of angular extension $\Delta\vartheta = 2\pi/N$. The fraction of energy leaving the i-th lamp of finite extension L which reaches an angular arc of finite extension $r_e\cdot\Delta\vartheta$ is:

$$F_{i\to j} = \frac{r_e}{L}\int_{\vartheta-\frac{\Delta\vartheta}{2}}^{\vartheta+\frac{\Delta\vartheta}{2}}\int_{\overline{x}_1}^{\overline{x}_2} dF_{dj\to di}d\vartheta \tag{4}$$

3.2. Radiative heating of PVC

Thermal irradiation I_r transferred at a given radius r can be expressed as:

$$I_r = I_{r_e}\cdot exp(-K_a\cdot(r_e-r)) \tag{5}$$

Equation 5 describes Lambert's law and relates the thermal irradiation I_r to the incident radiative flux I_{re} ; the radiative heating of semitransparent media is a volumetric phenomenon and can therefore be simulated as a heat source term. Based on the discussion in [15], the heat source term due to external lamps radiation in cylindrical coordinates can be expressed as:

$$q_g^{'''} = \left(\frac{1}{r}+K_a\right)\cdot I_{r_e}\cdot exp(-K_a\cdot(r_e-r)) \tag{6}$$

A similar form is used for the inner lamps:

$$q_{g\ Internal\ Lamps}^{'''} = \left(K_a-\frac{1}{r}\right)\cdot I_{ri}\cdot exp(-K_a\cdot(r-r_i)) \tag{7}$$

3.3. Finite element model

The local view factors were used in a finite element model set-up in COMSOL®, which accounts for rotation via a time-dependent boundary condition applied to a stationary domain. In the uniform radiation model, the heat source term depends on the radial coordinate only, while in the rotating cylinder model it depends both on the radial and angular coordinates of the reference system and is varies with a time period equal to $2\pi/\omega$, where ω is the angular velocity of the PVC tube. The local heat source intensity at any given time instant was computed by the solver recalling the MATLAB®function written for the calculation of the local view factors. Equation (8) describes the thermal energy transport in a solid medium under transient conditions, considering a generic 2D domain in cylindrical coordinates, with r the radial coordinate and ϑ the angular coordinate respectively.

$$\frac{1}{\alpha}\frac{\partial T}{\partial \tau} = \frac{q_g^{'''}(r,\vartheta,\tau)}{k} + \frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{1}{r^2}\frac{\partial^2 T}{\partial \vartheta^2} \tag{8}$$

A comparison with the case of uniform radiative flux was made in terms of the maximum temperature difference along the outer circumference, as well as the circumference defined by the mean radius and the inner circumference. The term corresponding to internal generation $q_g^{'''}$ include the contributions of both external and internal lamps and is expressed through Eqs. 6 and 7.

The starting temperature is uniform, $T_0 = 290\,K$, and the boundary conditions at the inner and outer wall are of convective and radiative heat transfer. Ambient air temperautre T_{air} equals T_0 and is constant.

4. Results

Simulations were run for pipes of three different outer radii, R_e, i.e. 62.5, 90 and 125 mm. The corresponding pipe thickness were 7.4, 10.7 and 10.8 mm respectively, from the smallest to the largest tube.

The normalized heat flux distribution along the outer circumference of a stationary pipe for each diameter and for different number of lamps was determined at first and the results are reported in Figs. 2(a) to 4(a). Data are plotted against the angular position $\theta \in [-\pi, \pi]$. The heat flux is normalized against the value of uniform heat flux (leading to $\bar{q} = 1 \forall \theta$ when radiation is uniform), which is obtained considering the power of each lamp, the number of lamps and the global view factor $F_{i\rightarrow j}$. For all cases, the minimum number of lamps gives the largest non-uniformities. Comparing pipe sizes, the highest values of the normalized heat flux are associated with the largest diameter. This is due to several reasons: each lamp has the same nominal power, the fewer the lamps, the lower the total power, the larger the diameter, the smaller the resulting heat flux. Also, for larger sizes, the distance between lamp and pipe, R_L, becomes smaller, therefore the amount of radiation per lamp impinging onto the pipe becomes larger, but is more concentrated. This also explains why some parts of the pipe are subject to zero radiative heat flux, since they do not see the lamp owing to the close distance between the two. As the pipe diameter decreases, the heat flux distribution becomes more even; the configuration closest to that for a uniform radiant source is the one corresponding to $R_e = 62.5\,mm$ and $N = 6$ lamps. When the number of lamps increases to $N = 8$ for $R_e = 62.5\,mm$ there is a stronger superposition in the fluxes from the different lamps which is the cause of the increase in the maximum values of the normalized heat flux, see Fig. 4(a).

In order to obtain heating conditions similar to those of a uniform radiative heat flux, the instantaneous local values of temperature along the circumference must be compared to the values which would result from uniform heating: the maximum difference between the two at a given instant is termed ΔT_{r_e}, and it can be shown that it decreases with time, reaching an asymptotic value which depends on ω, [7].

A critical angular velocity can then be defined as the minimum value of rotational speed which allows to maintain the maximum temperature displacement below a certain threshold. For a given oven configuration, the model can be used to determine this critical value for different tube geometries, after a maximum allowable temperature displacement (ΔT_{max}) along the outer circumference with respect to a perfectly uniform heating process has been established. To this aim, for each tube geometry and angular velocity investigated, ΔT_{max} must be compared to ΔT_{r_e}.

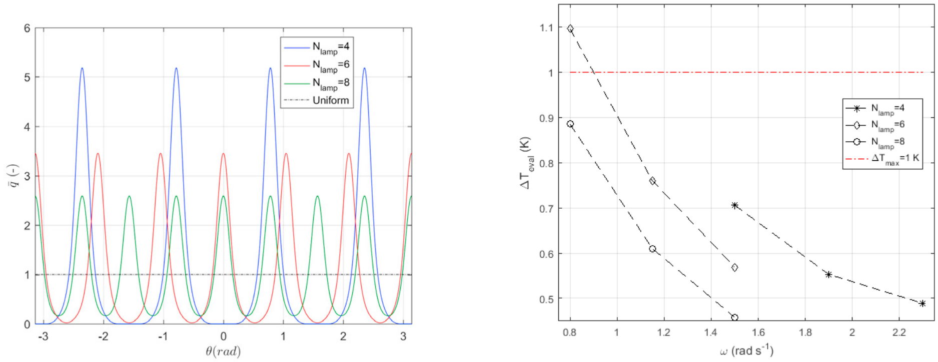

Fig. 2. (a) Normalized heat flux, $R_e = 125\,mm$; (b) Temperature difference.

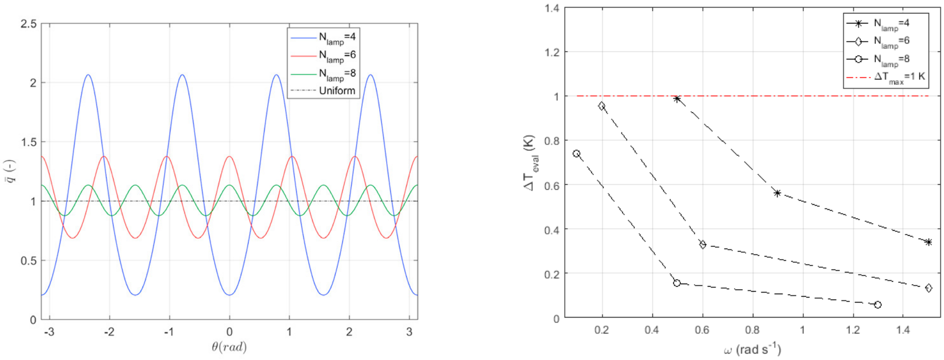

Fig. 3. (a) Normalized heat flux, $R_e = 90\,mm$; (b) Temperature difference.

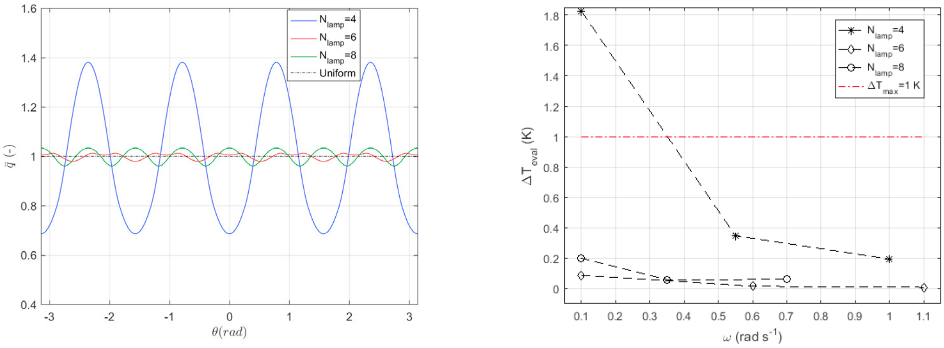

Fig. 4. (a) Normalized heat flux, $R_e = 62.5\,mm$; (b) Temperature difference.

In order to establish a significant instantaneous value of ΔT_{r_e} to compare to ΔT_{max}, a time interval $\Delta\tau = [\tau_0 - p, \tau_0 + p]$ has been considered, where p is the lamp facing period, defined as $p = 2\pi/(\omega \cdot N_{lamp})$, N_{lamp} is the number of external lamps in the oven and τ_0 is the instant of time in which the mean temperature along the outer circumference reaches the value $T_{off} = 433.15\ K$, which represents a credible value of the switch-off temperature of lamps, when these are controlled by a traditional pyrometer. The reference value is therefore calculated as $\Delta T_{eval} = max\{\Delta T(\tau)\}$, with $\tau \in \Delta\tau$. The value of ΔT_{max} can be established arbitrarily in the process design stage: in this work, a maximum temperature displacement $\Delta T_{max} = 1\ K$ was considered.

For each pipe and number of lamps, at least three different angular velocities ω have been considered, and the results are shown in Figs.2(b) to 44(b). As expected, the value of ΔT_{r_e} decreases with increasing angular velocity ω; the larger the pipe diameter, the higher the temperature non-uniformity at a given angular velocity. It can also be noticed that there is a sharp decrease in the values of ΔT_{r_e} with increasing ω for the largest pipe, whilst the trend becomes smoother as pipe diameter decreases and almost becomes independent of angular velocity for the smallest pipe and $N = 6$ and $N = 8$ lamps. This is the direct consequence of the increased flux uniformity discussed above: in the situation considered, the conditions are similar to those of even radiative heat flux and stationary pipe. As a last remark, it should be noticed that the values of angular velocity needed to get the condition $\Delta T_{eval} = \Delta T_{max}$ increase with pipe diameter; the phenomenon is readily explained considering the stationary flux plots, Figs. 2(a) to 4(a): for larger pipes, the circumferential non-uniformity is more pronounced, and larger rotational velocities are needed to offset it.

5. Conclusions

In this paper, the heating step of the end-forming process for polymeric pipes has been modelled and used to numerically determine the influence of the number of lamps on temperature uniformity and critical velocity. The model can be employed as a tool for determining the process parameters (e.g. angular velocity of the pipes) and the design (e.g. number of lamps) of the heating stage. For a given number of lamps, the minimum angular velocity to achieve temperature uniformity can be determined, or, for a maximum allowable angular velocity, the minimum number of lamps is found. It is also to be remarked that, in the cases analysed the threshold velocities associated to the smallest number of lamps is moderate at best, which means that fewer lamps can be employed reducing costs without consequences on the final characteristics of the pipe.

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