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ANNULAR FLOW OF HIGH-VISCOSITY EPOXY IN CIRCULAR PIPES

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ABSTRACT

A combined experimental and numerical investigation was done to study the flow of viscous epoxy propelled through circular tubes by compressed air. Epoxy moved through a pipe in annular flow and spread uniformly on the inner surface of the pipe, forming a thin, uniform coating. The objectives of the study were to determine the effect of varying process parameters such as air flow rate, temperature, and pressure, on the movement of epoxy within a pipe; to visualize epoxy flows through straight pipe sections and around elbows; and to determine how pipe geometry length and orientation affect epoxy flow.

High pressure air from a compressor was used to drive a slug of epoxy through clear poly-vinyl chloride (PVC) pipes. The epoxy was mixed from two parts, resin and hardener, and hardened in an irreversible exothermic reaction. A video camera was used to record the movement of the epoxy inside the pipe. Once the epoxy had hardened sections were taken through the pipe and the thickness of the coating measured. Tests were done varying a variety of experimental parameters including air pressure, airflow rate, piping configuration and epoxy temperature.

A one dimensional numerical algorithm was developed to model the fluid flow of epoxy and air within the pipe, the heat transfer between air, epoxy and walls, as well as the curing rate of the epoxy as it is moving alongside the pipe. Results from the model were used to predict the epoxy front velocity and coating thickness and were compared to the experimental observations.

Heating the epoxy was found to slow its motion, since the epoxy sets faster at a higher temperature and its viscosity becomes greater. Before curing occurs, the viscosity decreases as the temperature is increased. The viscosity then increases when hardening takes place. The coating was significantly thicker at the bottom of a horizontal pipe than at the top due to sagging of the epoxy coating after it had been applied, resulting in flow from the top to the bottom of the pipe. Sagging could be reduced by maintaining airflow until curing was almost complete and the epoxy had hardened enough to prevent it from moving easily. The most important parameters controlling the speed of the epoxy and coating thickness were the air flow rate and temperature, since they determine the shear forces on the epoxy layer and the rate at which the epoxy cures. Raising air temperature increases the reaction rate and therefore decreases the time required for the epoxy to cure inside the pipe.

INTRODUCTION

Typical water pipelines in residential and commercial buildings have limited lifespan. Depending on the quality—soft or hard—of water, degradation of pipelines creates corrosion or blockage problems. Traditionally these pipes require replacement at the end of their service life, which is a lengthy and costly process. An alternative method, the internal rehabilitation of pipelines, is currently done by applying a thin layer of protective coating, which contains non-toxic chemically-resistant epoxy to the existing pipes. The process involves three steps. First, pipes are drained and dried with hot air. Next, abrasive particles are blown through them to remove any scale on their walls. Finally a cylinder of liquid epoxy is attached to the pipe entry and blown through the pipes using compressed air. The liquid forms a uniform layer on the walls and cures until it is hard. This method eliminates the need to remove any embedded pipes, reducing both capital and labor costs. However, the process is difficult to control and results vary widely depending on pipe size and geometry, ambient temperature and process parameters. This project was undertaken to give a better understanding of the parameter that control movement of epoxy within pipes.

The objectives of the study were:

- To determine the effect of varying important process parameters, such as air flow rate, temperature, and pressure, on the movement of epoxy within a pipe.
- To visualize epoxy flows through straight pipe sections and around fixtures such as 90 degree elbows and T-

junctions.

- To determine how pipe length, material, and orientation affect epoxy flow.
- To develop a model capable of predicting the rate of epoxy movement in pipes.

NOMENCLATURE

A	[s^{-1}]	Frequency factor
C_p	[W/kg-K]	Heat capacity
E_a	[J/mol]	Activation energy
f	[-]	Friction factor between air and epoxy
h	[W/m^2-C]	Convection heat transfer coefficient
H	[m]	Thickness of epoxy
H_R	[J/kg]	Heat of reaction
k	[W/mK]	Thermal conductivity
K_r	[s^{-1}]	Reaction constant
n	[-]	Order of reaction
Nu	[-]	Nusselt Number
P_r	[-]	Prandtl Number
q	[W/m^3]	Volumetric heat generation
Q	[m^3/s]	Volumetric flow rate
R	[m]	Pipe radius open to air
R_a	[-]	Rayleigh Number
R_u	[J/mol-K]	Universal Gas Constant
t	[s]	Time
T	[K]	Temperature
V	[m/s]	Velocity
x	[m]	Cartesian axis direction
y	[m]	Cartesian axis direction

Special characters

α	[-]	Curing degree of epoxy
τ_0	[kg/m^2]	Shear Stress
δ	[m]	Thickness
ρ	[kg/m^3]	Density
μ	[kg/s.m]	Dynamic viscosity

EXPERIMENTAL APPARATUS AND METHOD

The epoxy used in tests (Elastochem Special Chemicals Inc., Brantford, Ontario), was a custom formulated type designed specifically for lining of pipes. Like many other commercially available epoxy glues, it is to be mixed from two parts, the resin and the hardener, at a ratio of 3:1. The hardening of epoxy is an irreversible exothermic reaction that cures over a period of time; its rate is determined by the temperature at which the two parts are mixed and the subsequent temperature during the curing of epoxy.

Figure 1 shows a schematic diagram of the experimental apparatus built. High pressure air from the compressor flows through a flow meter and pressure gauge and passes through the length of pipe to be coated. Prior to the insertion of epoxy, valve 1 and 3 are adjusted to obtain the desired pressure and flow rate while valve 2 is left fully open. Valve 2 is then closed. The epoxy is preheated to the required temperature and premixed to specified condition, and placed inside the shot tube. Valve 2 is again fully opened, and a video camera used to record the movement of the epoxy inside the pipe until the pipe is coated entirely. Thermocouples were placed along the length of the pipe and temperatures recorded using a data acquisition system. Tests were done varying a variety of experimental parameters (air pressure, airflow rate, pipe geometry, post treatments, epoxy temperatures, etc).

Flow visualization was one of the most important goals of the experiments, so that measurements of epoxy velocity and displacement could be made. Clear poly-vinyl chloride (PVC) pipes with inner diameter of 15.29 mm (1/2 in., Sch. 40), suitable for relatively high-pressure applications, were used (see Figure 2). The PVC pipes, when mated with clear fittings such as 90 degree bends (elbows) and T-junctions (tees), also allowed us to create customized piping geometry.

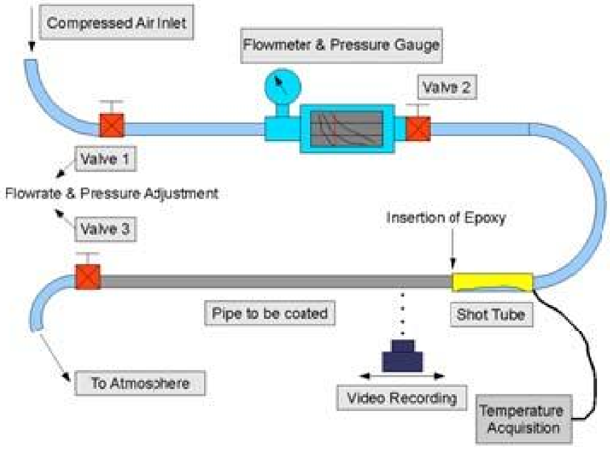

Figure 1 Experimental apparatus

Video recording of epoxy flow on the clear PVC pipes was done to measure the speed at which the epoxy travels over the length of pipe. A digital video camcorder operating at a standard 30 frames per second was used. The motion of epoxy was slow enough that the camera could be moved manually along the length of the pipe to track the position of the front edge of the epoxy layer.

Thermocouples were placed along the length of the pipe and wall and air temperatures recorded using a data acquisition system (National Instruments, Austin, TX)

Figure 3 shows successive stage of epoxy advancing down the length of a pipe. The scale is in inches, measured from the entrance of the pipe. Figure 4a shows the pipe just before the start of the experiment, and Figs 3b and c show the advancement of the epoxy once air flow had started. Figure 3d shows the thinning of the epoxy layer as air was blown through the pipe.

Figure 2: Fittings and 15.29 mm diameter pipes used

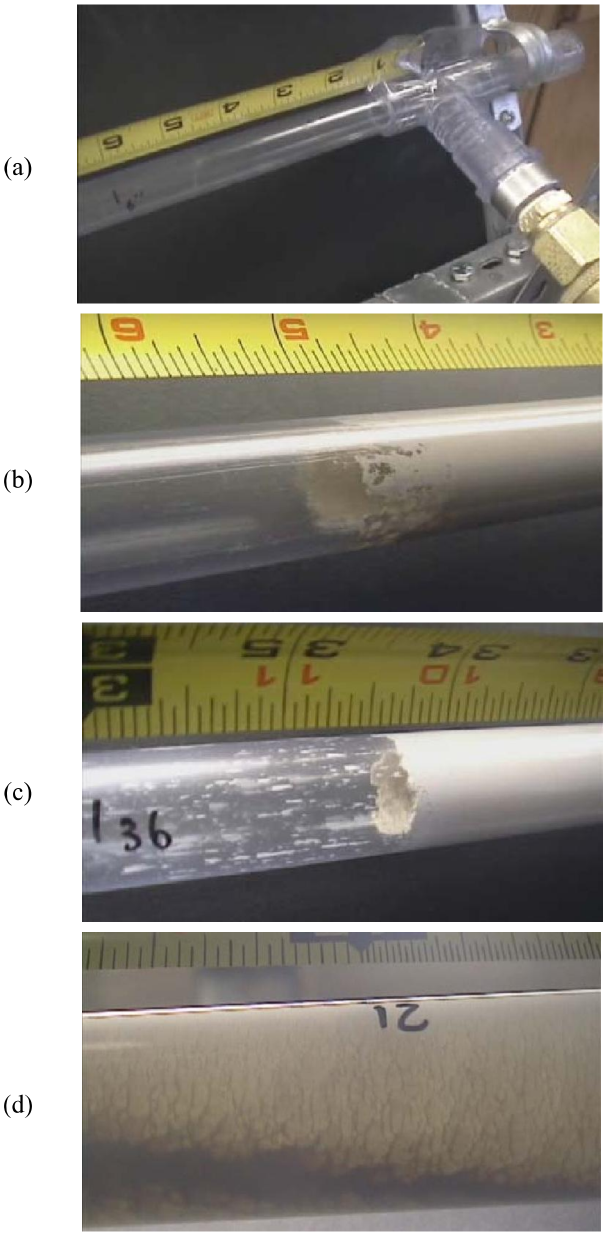

Figure 3 Epoxy travelling inside a15.29 mm inner diameter pipe. The scale is in inches

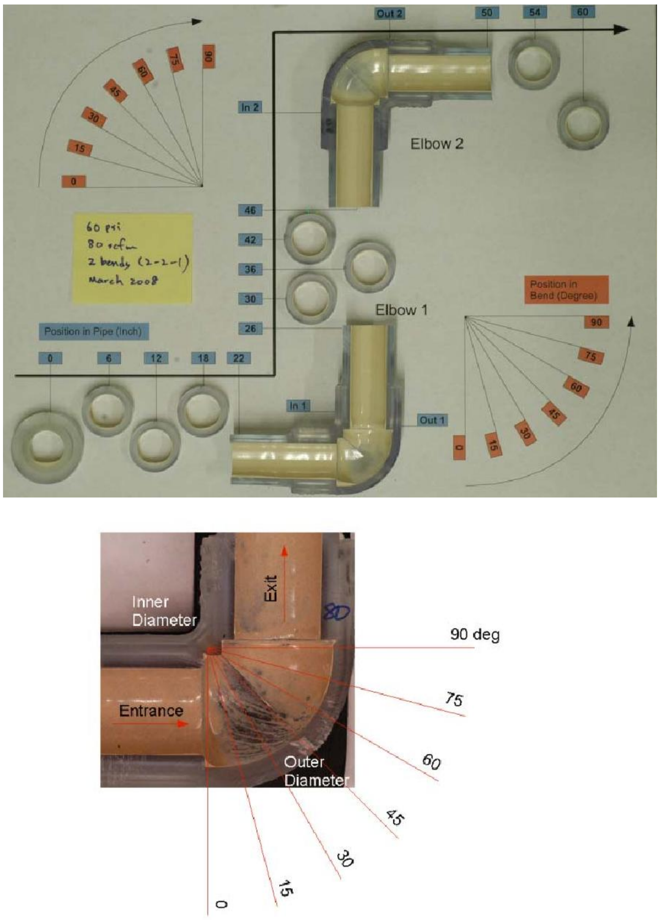

Figure 4 Layout of samples ready for measurement and in-bend measuring points.

Once the epoxy had hardened sections were taken through the pipe at 152.4 mm (6 in) intervals, as shown in Fig 4. The thickness of the coating in each section was then measured by placing the section under a microscope, photographing the coating, and using an image analysis program to measure the thickness of the coating at different locations around the periphery of the pipe. For horizontal straight sections, two points of interest, namely the top and bottom of the sample, are sufficient to show the largest variation in thickness at any point along the pipe; for vertical sections, two arbitrary points 180° apart on the perimeter of the ring are sampled to seek greatest variation in thickness. When examining elbow fittings, thickness measurements are taken, measuring from the entrance, every 15° into the elbow, both on the inner and outer radii.

Figure 5 shows measurements made from videos of the position of the leading edge of the epoxy as a function of time for three different airflow rates: 37.8 L/s (80 standard cubic feet per minute (SCFM)), 47.2 L/s (100 SCFM) and 56.6 L/s (120 SCFM). The velocity increased significantly with airflow rate, reducing the time required to coat a 1.52 m (5 ft) length of pipe. The displacement is non-linear: the epoxy travels much faster in the earlier stages and becomes progressively slower as the layer becomes thinner and shear forces increase.

Figure 6 shows the epoxy displacement as a function of time for two initial temperatures of the epoxy: 43.3°C (110 °F) and 51.7°C (125°F). Heating the epoxy slows down the motion, since the epoxy sets faster at a higher temperature and its viscosity becomes greater.

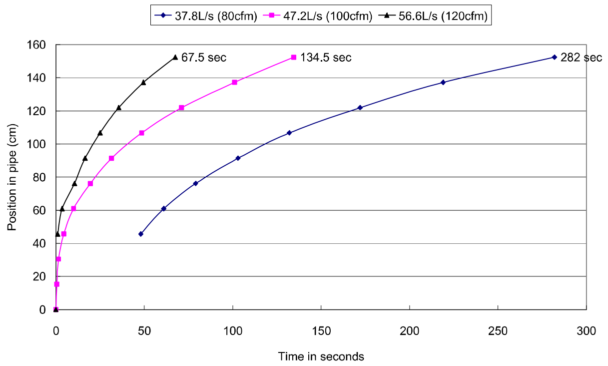

Figure 5 Displacement of epoxy as a function of time for three different airflow rates: 37.8 L/s (80 SCFM), 47.2 L/s (100 SCFM) and 56.6 L/s (120 SCFM).

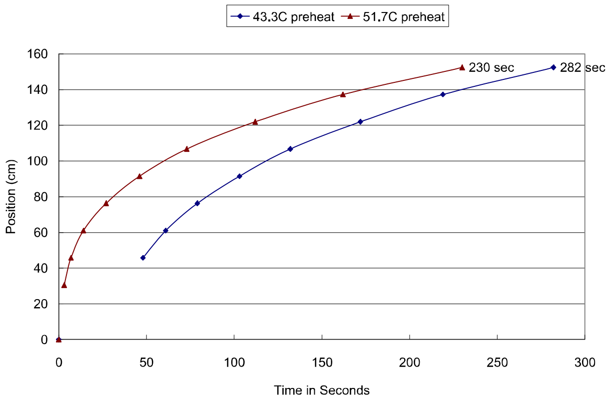

Figure 6 Displacement of epoxy as a function of time for two initial epoxy temperatures: 43.3°C (110 °F) and 51.7°C (125°F).

Figure 7 shows measurements of coating thickness at 15 cm (6 in) intervals along the length of the pipe, at both the top and bottom of the horizontal pipe for three different flow rates. The coating was significantly thicker at the bottom of the pipe (average thickness 0.88 mm), than at the top (average thickness 0.35 mm) The difference was attributed to sagging of the epoxy coating after it had been applied, resulting in flow from the top to the bottom of the pipe.

To prevent sagging of the epoxy after coating, tests were done in which the air flow was kept on for 5 or 15 minutes after the end of coating, to give the epoxy time to set.

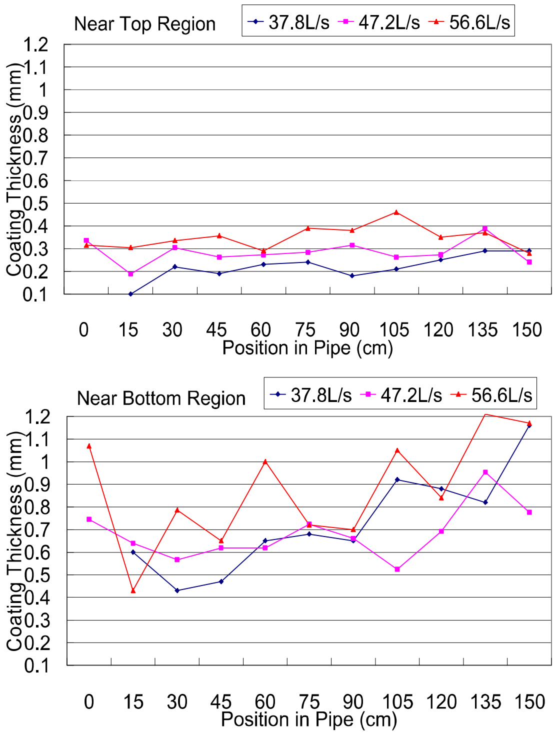

Figure 7 Coating thickness measured along the length of the pipe at both the top and bottom of the pipe.

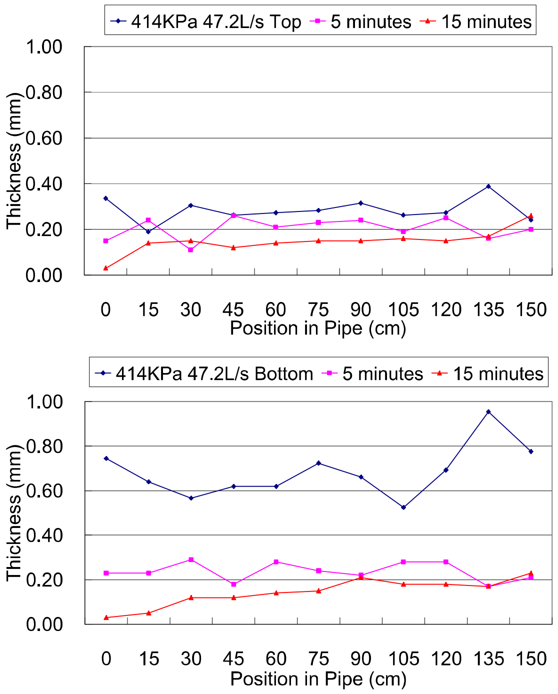

Figure 8 Coating thickness measured along the length of the pipe, at both the top and bottom of the pipe, with air flow maintained for 0, 5 or 15 min after coating.

Figure 8 shows the coating thickness at the top and bottom of the pipe for 0, 5 and 15 minutes of post-treatment. As one would intuitively expect, the additional air constantly shears the epoxy liner out of the pipe and decreases the overall thickness of liner both on the top and bottom region of pipe. However, due to the air constantly flowing inside the pipe, epoxy was given more time to cure and be held in place upon completion of post treatment. As a result, the thickness differences between the top and bottom regions become less apparent as the duration of post treatment increases.

Tests were done on bends, which have proved the hardest to coat in practice. Figure 9 shows a photograph of an elbow after coating and the variation of thickness as a function of position. Epoxy accumulates near the entrance to the bend, but becomes much thinner after the 45° position.

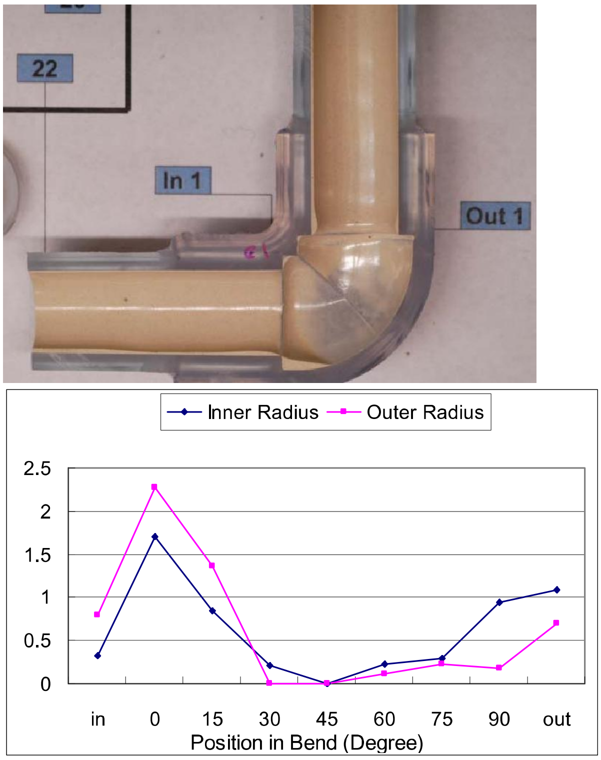

Figure 9: Photograph of an elbow sample (top) and its thickness distribution (bottom).

Additional tests were done with copper pipes to confirm that the results obtained with PVC pipes were applicable to them. Tests were done with both horizontal and vertical pipes and it was found that orientation did not have a significant effect on the rate at which epoxy moved.

NUMERICAL METHOD

In order to perform numerical simulation to predict the epoxy position and thickness in the pipe, there were basically two choices. The first choice was to perform computational flow dynamic simulation, solving Navier-Stokes equation and tracking the free surface front of the epoxy. This could be done using a three or two-dimensional algorithm. However, since the viscosity of the epoxy is very high (4000-10000 times of water) and the length scale of the problem is large (1.5 – 10 m of pipe) the calculation time to track the epoxy front would be such large that there is no benefit of modeling the process at all.

On the other hand, during the course of experiments, in which the clear Plexiglas ½ inch pipes were lined with the epoxy under controlled conditions, it was observed that, except for the first short length of the pipe (less than 30 cm), the movement of the epoxy is well defined. That is to say that the movement of the epoxy is the result of shear forces exerted by the air flowing in the pipe.

For this reason, it was decided to develop a one dimensional model to predict the epoxy behavior in the pipe within a reasonable time and acceptable accuracy.

ONE-DIMENSIONAL FLOW MODEL

In order to simulate epoxy thinning and movement in the pipe, one can use the model of annular flow presented in Ref. [1] and illustrated in Figure 10. A fixed volume of epoxy is assumed to be distributed in an annulus around the inside surface of the cylindrical pipe, with air flow along the central portion. Once airflow starts, shear forces move the epoxy forward in the pipe and the thickness of the epoxy layer decreases as it moves forward. Finally an epoxy layer of uniform thickness will cover the entire inner surface of the pipe.

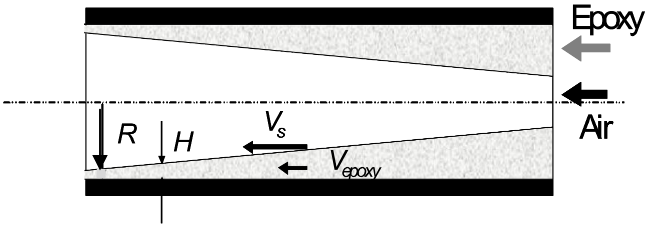

Figure 10: Simple model to show the thinning of the epoxy in the pipe due to share forces imposing from air

Since it is assumed that the air and epoxy flow inside the pipe is symmetric with respect to the pipe axis, one can use a one dimensional model to calculate the velocity of the epoxy and its thickness for half of the pipe. Once the velocity of the epoxy inside the pipe is determined, it becomes possible to estimate the total time it takes for epoxy to travel the length of the pipe and coat it entirely.

GOVERNING EQUATIONS: FLOW MODEL

Shear Rate

The shear stress relation, τ_0, acting from air flow on the epoxy layer can be expressed as:

$$\tau_0 = {}^{1}\!/_{2}\, f \rho_{air} \left[\frac{Q_{air}}{\pi R^2}\right]^2 \tag{1}$$

where ρ_{air} is the density of the air, f the friction factor between air and epoxy, Q_{air} is the flow rate of air, and R the radius of the pipe open to air flow. The relation between the shear stress and the viscosity of the epoxy is:

$$\tau_0 = {}^{\mu_{epoxy} V_s}/_{H_{epoxy}} \tag{2}$$

where $\boldsymbol{\mu_{epoxy}}$ is the dynamic viscosity of the epoxy, $\boldsymbol{V_s}$ is the velocity of the epoxy at the interface between air and epoxy, see Figure 10, and H_{epoxy} is the local thickness of the epoxy.

Couette flow

Assuming that the epoxy thin film exhibits planar Couette flow, the average velocity of the epoxy, V_{epoxy} can be related to the interface flow velocity of V_s by the following expression, Ref [1]:

$$V_s = \frac{1}{2} V_{epoxy} \tag{3}$$

By combining equations (1) to (3), one can find the average epoxy velocity at each location from the following relation:

$$V_{epoxy} = \frac{1}{4} \frac{H_{epoxy}}{\mu_{epoxy}} f \rho_{air} \left[\frac{Q_{air}}{\pi R^2}\right]^2 \tag{4}$$

The density of air in this equation is a function of air pressure and temperature. The viscosity of the epoxy is a function of epoxy temperature, which in turn depends on the its initial temperature, air temperature and the curing reactions inside the epoxy layer.

GOVERNING EQUATIONS: HEAT TRANSFER MODEL

Since the viscosity of epoxy will play an important role in calculating its velocity in the pipe, it is essential that a heat transfer model is also developed. Since we assume a one-dimensional model for flow, the heat transfer equations must be also one dimensional.

Preliminary experiments in which the temperature of the pipe and the compressed air were measured along the length of the pipe during epoxy lining showed that the temperature of the pipe remains almost constant along the pipe length. This is an indication of the heat transfer between the epoxy, pipe wall and the compressed air, is only significant in the radial direction. Figure 11 shows a simple schematic of the one dimensional model. The x coordinate lies along the axis of the pipe and the y coordinate is in the radial direction in the pipe.

Thermal conduction equation

Heat conduction inside the epoxy layer is described by the equation:

$$\left(\rho C_p\right)_{epoxy} \frac{\partial T}{\partial t} = \frac{\partial}{\partial y}\left(k_{epoxy}\frac{\partial T}{\partial y}\right) + \frac{\partial q}{\partial t} \tag{5}$$

where y is measured within the epoxy thickness H. $C_{p_{epoxy}}$ is the thermal heat capacity of the epoxy, k_{epoxy} is the thermal conductivity of the epoxy and q is the heat generated due the exothermic reactions inside the epoxy.

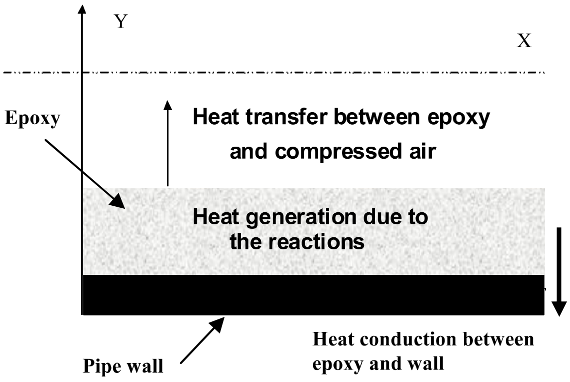

Figure 11. Schematic presentation of the one dimensional heat transfer in the epoxy layer

Curing rate

Heat generation inside the epoxy, q, is related to the curing rate via the following relation:

$$\frac{\partial q}{\partial t} = \rho_{epoxy} H_R \frac{\partial \alpha}{\partial t} \tag{6}$$

where H_R is the heat of reaction for the epoxy and ${}^{\partial\alpha}/_{\partial t}$ is the curing rate of the epoxy. Curing rate of the epoxy can be obtained from the following relation, see Ref [2,3]:

$$\frac{d\alpha}{dt} = K_r(1-\alpha)^n = Ae^{{}^{-E_a}/_{R_u T}}(1-\alpha)^n \tag{7}$$

K_r is the reaction constant and is usually assumed to be of the Arrhenius form. A is the frequency factor, R_u is the universal gas constant, E_a is the activation energy, n is the order of the reaction. The epoxy curing properties were measured using a Dynamic Scanning Calorimeter (DSC) and the coefficients in equation (7) were obtained by analyzing the curing rate of the epoxy (also see Ref.[2]).

Heat transfer equation

The heat transfer between epoxy layer and the compressed air can be described with the following relation:

$$\dot{q}_{conv} = K_x \frac{\partial T}{\partial x} = h_{air}(T - T_{air}) \tag{8}$$

where $\dot{q}_{conv}$ is the rate of convection heat transfer between air and the epoxy and h_{air} is the convection heat transfer coefficient $({}^{W}/_{m^2.C})$. The heat transfer coefficient between air and epoxy depends on the physical properties of these two materials as well as the temperature and velocity of the air in the pipe. In heat convection studies it is common practice to non-dimensionalize the heat transfer coefficient h_{air} with the Nusselt number, defined as:

$$Nu = h_{air} \frac{\delta}{K_{air}} \tag{10}$$

where K_{air} is the thermal conductivity of air, δ is the characteristic length which can be assumed to be the thickness of the epoxy. Nusselt number, Nu, for heat transfer in a horizontal cylinder can be obtained from, Ref [4]:

$$Nu = \left[0.6 + \left(\frac{0.387{R_a}^{1/6}}{\left(1+\left(\frac{0.559}{P_r}\right)^{9/16}\right)^{8/27}}\right)\right]^2 \tag{11}$$

where R_a and P_r are the Rayleigh and Prandtl numbers, respectively. The Rayleigh number is the product of the Grashof and Prandtl number (Ref [4]).

Initial and Boundary Conditions

In order to solve equations (5) to (8), the initial temperature of the epoxy, the initial curing degree, as well as the air temperature and pipe wall temperature are needed. The initial temperature of the epoxy was measured in experiments. Also, based on some preliminary experiments, it was shown that the pipe wall temperature reaches the air temperature within a few seconds of the start of the experiments. The initial degree of curing is assumed to be zero.

RESULTS

The one dimensional numerical algorithm was applied to model epoxy movement inside the pipe for the experiments performed under controlled conditions.

In Figure 12 simulation results showing the position of the epoxy front in the pipe as a function of time are compared with the experimental results shown in Figure 5 are shown. The pipe diameter and length were 12.7 mm and 1.5 m respectively. The initial temperature of epoxy in this set of experiments was 43.3°C (110 °F) and the air temperature was approximately 25°C. In another simulation, the initial temperature of epoxy was raised to 51.7°C (125°F) and simulations were repeated for an airflow of 37.8 L/s (80 SCFM). A comparison with experimental results (Figure 6) is shown in Figure 13 with good agreement.

In Figure 13, simulation results and the comparison with the experimental measurements with two bends along the length and a total length of 1.5 m is shown. The flow rate of blowing air is 37.8 L/s. In order to account for fittings such as bends and tees in the piping system, the corresponding friction factors were calculated and the air pressure adjusted accordingly. The simulation also accounted for the post treatment to reduce sagging of epoxy (shown in Fig. 8) in which after the epoxy reached the end of the pipe the air flow rate was reduced to 21.26 L/s (45 SCFM) but maintained for 5 min until the epoxy sets.

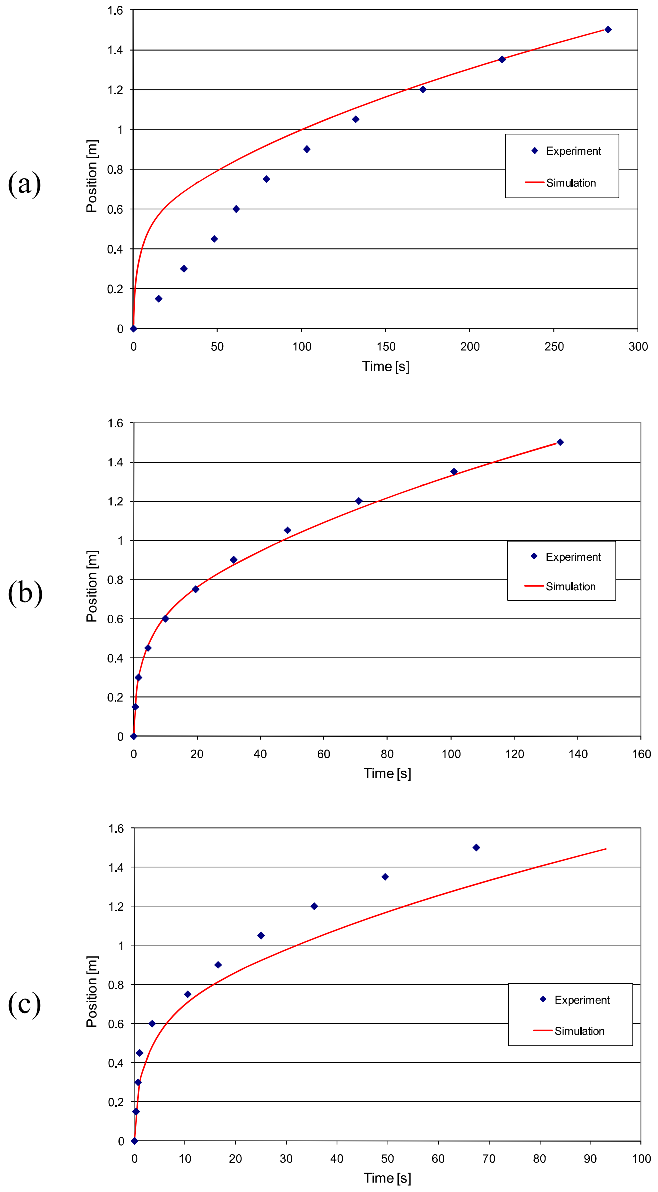

Figure 12 Simulation results, predicting the epoxy displacement shown in Figure 5, for three different airflow rates, from top: (a) 37.8 L/s (80 SCFM), (b) 47.2 L/s (100 SCFM) and (c) 56.6 L/s (120 SCFM).

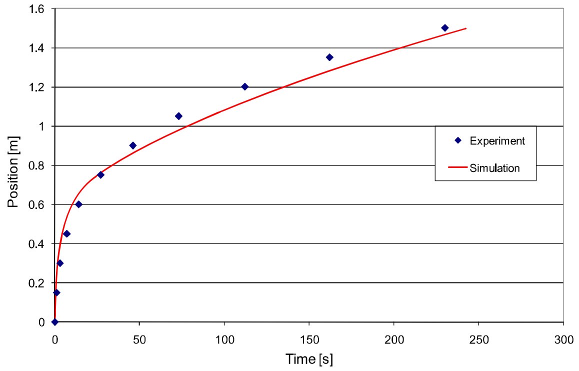

Figure 13 Simulation results and comparison with experiment, predicting the epoxy displacement shown in Figure 6, for airflow rate of 37.8 L/s (80 SCFM) and initial epoxy temperature of 51.7°C (125°F).

Figure 14a shows the epoxy position in the pipe versus time during lining. In Figure 14b, simulation results showing the epoxy thickness and velocity in the pipe versus time are shown. In this figure, a sudden change in the velocity of the epoxy occurs when the post lining process starts. Since during post lining air flow rate is usually lower than the flow rate used during lining, the epoxy velocity is also reduced. Average coating thickness was calculated by assuming that the initial volume of epoxy was spread uniformly over the inner surface of the pipe at each instant. As shown in Figure 14c, the epoxy thickness at the inlet of the pipe was somewhat greater but remained uniform over most of the pipe length. In this experiment the average epoxy thickness was about 0.4 mm. whereas the simualtion gave a value of 0.405 mm.

Simulations were done to determine the effect of varying air temperature, pressure and flow rate of air

Figure 15 shows the epoxy displacment versus time for a 12.7 mm diameter, 1.5 m long PVC pipe at different air temperatures. Air temperature affects the viscosity of the epoxy and therefore its motion. The curing rate of the epoxy also increases exponentially with temperature. As can be seen from Figure 15, by increasing the air temperature at a constant flow rate, the velocity of the epoxy in the pipe inceases and therefore the time for lining the pipe decreases. So, it is very important to control the air temperature under different ambient conditions. For example, in summer when air temperature is high lining will take place very fast and may not give the time to epoxy for curing. On the other hand, on colder days lining will take very long and also the lower viscosity of the epoxy may not allow it to completely coat the inside of the pipe before it sets.

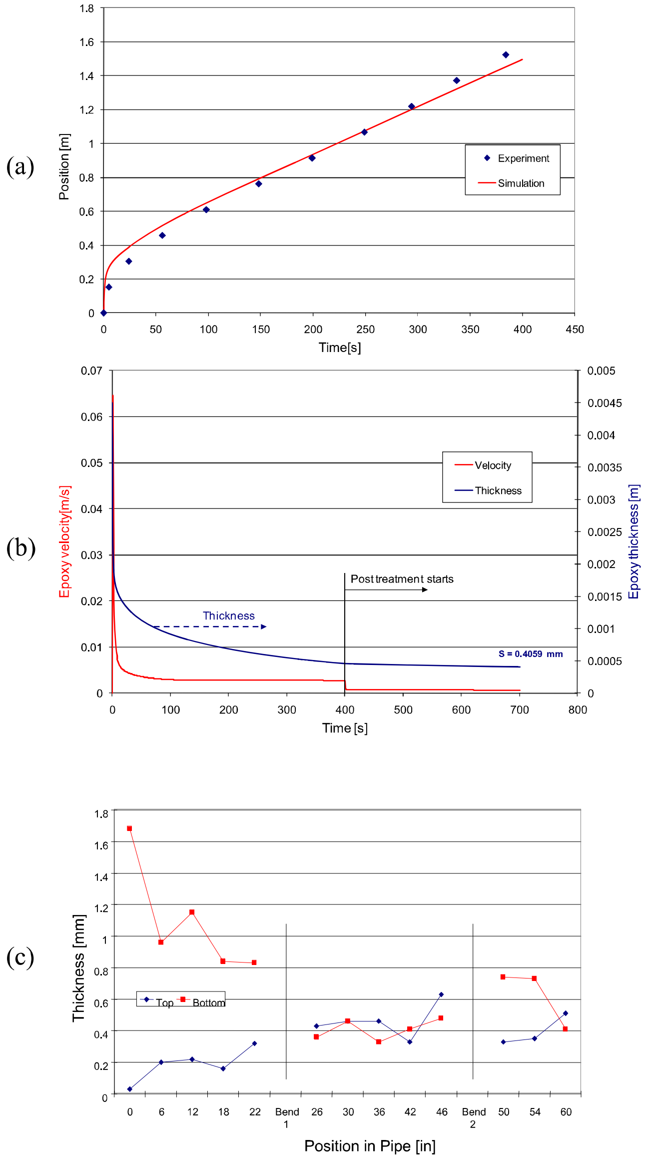

Figure 14. Simulation results and comparison with the experimental measurements for a 1.5 m pipe with two bends, air flow rate 37.8 L/s (80 SCFM). The results from top: (a) Epoxy front displacement; (b) simulated epoxy front velocity and average epoxy layer thickness variation with time; (c) Experimental measurements of the epoxy thickness at the top and bottom of the pipe.

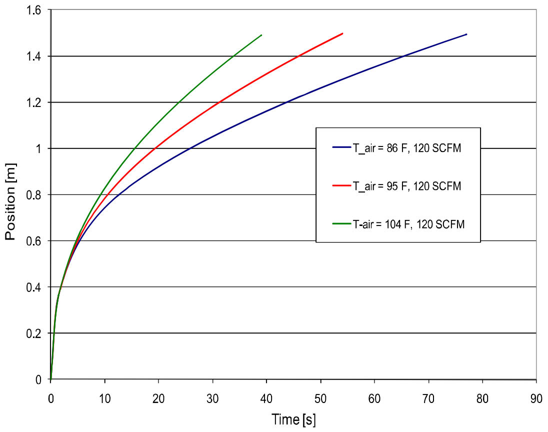

Figure 15. Effect of air temperature on the epoxy displacement.

In Figure 16, the simulation results for epoxy displacement for two different air flow rates and pressures, at constant air temperature, are shown. As can be seen, the effect of flow rate is much more prominent than the effect of pressure, as can also be seen from Equation (4).

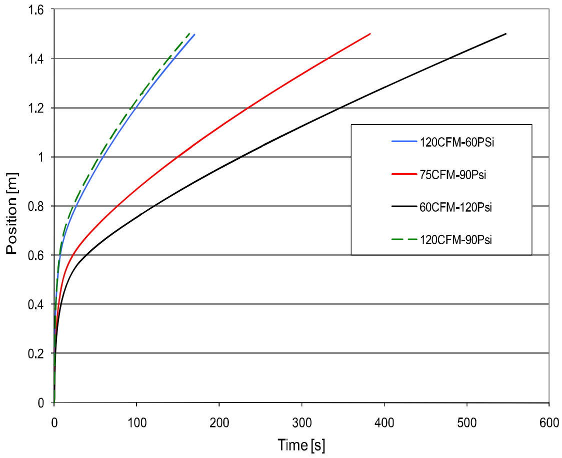

Figure 16. Effect of air flow rate and pressure on the epoxy displacement.

CONCLUSION

The process of pipe lining in small pipes (15 mm in diameter) using a thermoset resin was studied both experimentally and analytically. It was found that the compressed air flow rate and temperature play the most important roles in determining pipe lining time and coating thickness. The air temperature must be such that it allows for the epoxy to flow easily inside the pipe and at the same time let the epoxy to start curing.

The thickness of the epoxy on the wall is not uniform and varies along the length of the pipe as well as at the top or bottom of the pipe cross section. That is due to the sagging of the epoxy which is not fully cured. To reduce sagging a post lining step must be performed with a reduce air flow rate to help set the epoxy.

In a piping system with bends, tests with both horizontal and vertical pipes showed that orientation did not have a significant effect on the rate at which epoxy moved.

A one dimensional numerical algorithm was developed to model flow of epoxy and air within the pipe, the heat transfer between air, epoxy and walls, as well as the curing rate of the epoxy as it is moves through the pipe. The model was used to predict front velocity and thickness of the epoxy. The good agreement between the numerical results and the experimental measurements suggested it is feasible to use a one-dimensional model for predicting the epoxy behaviour in the pipe during the lining and post lining procedures.

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