Water flow through a 20-pore perforation plate in vessels of *Liquidambar styraciflua*

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Abstract

The flow of water through perforation plates of *Liquidambar styraciflua* vessels was studied through a computational fluid dynamics approach together with a large-scale physical model of the perforation plate. For the computational approach, a finite elements model was constructed of a 20-pore perforation plate and the region around the plate. Solutions of this model describe pressures and velocities for points within the model. The pressure gradient within the pores of the plate was about 40-fold greater than for regions away from the plate. However the influence of the plate on flow extends for only a very short distance before and after the plate. Overall, the perforation plate in this model was calculated to account for 23% of the total resistance to flow encountered along the vessel. Calculations from the physical model provided a similar estimate of 21% for the contribution of the perforation plate to flow resistance.

Key words: Perforation plate, vessel, water flow.

Introduction

Water flow along the stems of many plant species occurs through conduits called vessels, which are made up of a series of individual cells called vessel members or elements. For certain species, remnants of each cell’s end walls are present in the form of a series of parallel bars across the vessel, producing a structure called a scalariform perforation plate. The significance of the perforation plate as an obstruction to water flow remains an area of active inquiry. It has been shown that structures of this type occur primarily in plant species from high elevation or high latitude locations (Baas, 1976). Their present occurrence may due to a lack of selection pressure for their removal (Baas and Schweingruber, 1987). If perforation plates provide a source of resistance to flow, perhaps they have some other significant function such as the trapping of air bubbles that develop when cellular water freezes at locations experiencing low seasonal temperatures (Zimmermann, 1983). Thus the author has been interested in determining the extent to which perforation plates obstruct flow along vessels of plant stems.

A previous study utilizing a computational fluid dynamics approach applied to perforation plates of *Liriodendron tulipifera* having five pores suggested that a plate of such structure was not very significant as a source of resistance (Schulte and Castle, 1993a, b). Although the plate accounted for half of the flow resistance for the region near the plate, when the added resistance of the regions between plates (where only the cell wall resistance appears) was considered, the plate accounted for only about 8% of the total resistance to flow along the vessel.

The present work considers a more complicated plate model of *Liquidambar styraciflua* having 20 pores. Although pores in the perforation plates of this species are narrower than those of *Liriodendron tulipifera* cited earlier, the plate lies at a smaller angle relative to the axis of the vessel. Thus, the pores are spread out over a greater distance along the vessel—the flow will pass through narrower pores but there are more pores. In addition, a physical model was created that included a large-scale replica of a 20-pore perforation plate. Measurements of flow velocity and pressure drop in these models were used to estimate the degree of obstruction that could be attributed to the plate.

Materials and methods

Computational model

A finite element model of a *Liquidambar styraciflua* vessel element perforation plate was developed and solved with a fluid
dynamics software package (FIDAP Version 7.6, Fluid Dynamics International, Evanston, IL, USA) running on a Silicon Graphics Inc. Power Challenge L computer (4 R8000 CPUs with 512 MB of memory and 12 GB of disk storage) that is part of the WM Keck Computational Physics Laboratory in the Department of Physics. This approach solves the Navier–Stokes equation describing the flow of incompressible Newtonian fluids for arbitrarily defined regions (Munson et al., 1990; Schulte and Castle, 1993a).

The construction of the element mesh (Fig. 1) for the region around and including the perforation plate was based on scanning electron micrographs of the xylem from 1-year-old stems of Liquidambar styraciflua. The modeled cell was 25 μm in diameter with a perforation plate having 20 pores. The perforation plate was inclined 13 degrees relative to the vessel axis and had a total length of 114 μm. The plate pores were 4.8 μm wide and the bars separating the pores were 0.85 μm wide (in plane of plate) and 1.31 μm in depth (perpendicular to plate). The length of a typical vessel element was taken from previous work (Schulte et al., 1989) as 727 μm.

The physical dimensions for the computational models were scaled to minimize numerical rounding-up errors that could result from the small dimensions of the actual vessel elements. The scaling process was applied to the basic units of kg and m; each being multiplied by 1E6. For example, the diameter of the model in metres of 25E−6 was scaled to 25, and the peak inlet velocity component along the axis in m s⁻¹ of 0.001 became 1000. Pressure in pascals does not change because for the fundamental quantities of pressure (kg m⁻¹ s⁻²), the scaling changes cancel. Models were solved with a velocity boundary condition at surfaces defining the wall of the cell and the bars of the plate set to zero. The inlet velocity was set as a paraboloid whose peak velocity at the centre was 1.0 mm s⁻¹, a typical value for flow through vessels of woody species (Zimmermann, 1983). The fluid density was 998 kg m⁻³ and the fluid viscosity was 1.002E−3 Pa s.

Solutions of the model provided velocity components and pressures at the corners of all elements in the model. The model was gradually refined to increase the density of elements in regions around the perforation plate in order to test the adequacy of the finite element mesh. A denser mesh (closer spacing between nodes) provides a more accurate solution, but increases the requirements for computer memory and computation time.
Flow through perforation plates

The physical model of a Liquidambar styraciflua vessel. The test section containing the perforation plate was constructed from a 2 m length of 38.1 mm inner diameter plexiglas. Other sections were constructed from 38.1 mm inner diameter PVC pipe. Valves (labelled ‘V’) could be used to adjust the flow rate through the model. The pressure transducers (labelled ‘P’) were connected with tubing (indicated by dashed lines) to taps in the pipe wall spaced at a 1 m distance. Also shown is a calibration section used for estimating the fluid viscosity. Unlabelled boxes indicate smooth-walled couplings. The fluid level in the head tank was about 0.8 m above the level of the test section. For visualization purposes, the model is drawn as though the test and calibration sections are at different heights. In reality, the right-most pipe segment is horizontal and the test and calibration sections are at the same level.

The effect of the perforation plate on flow through the vessel was calculated from pressure drops through the model cell:

\[
\text{Plate effect} = \frac{\Delta P_{\text{plate}}}{\Delta P_{\text{cell}}} = \frac{\Delta P_{\text{mod}} - \Delta P_{\text{no plate}}}{\Delta P_{\text{mod}} + \Delta P_{\text{rem}}}
\]

where \(\Delta P_{\text{plate}}\) is the pressure drop due to the plate alone and is calculated from \(\Delta P_{\text{mod}}\), the pressure drop through the model with a plate, and from \(\Delta P_{\text{no plate}}\), the pressure drop for the model without a plate. The total pressure drop along a vessel element with one perforation plate \((\Delta P_{\text{cell}})\) is calculated from \(\Delta P_{\text{mod}}\), the pressure drop for the model with a plate, and \(\Delta P_{\text{rem}}\) the pressure drop for the remainder of the vessel element not included in the model. The plate effect is therefore the fraction of the total pressure drop along a vessel element that may be attributed to the perforation plate alone.

**Physical model**

A physical model (Fig. 2) of the region around a 20-pore vessel perforation plate was constructed from 38.1 mm diameter plexiglas pipe. A thin sheet of plexiglas (1.6 mm thick) was machined to match a perforation plate template drawn from the same specifications used in constructing the finite element mesh for the computational model (Fig 1). This perforation plate sheet was then cemented into the model pipe cut at a 13° angle relative to the long axis of the pipe. Fittings for pressure measurements were threaded into the pipe at a 1 m spacing centred around the perforation plate and also along an unobstructed pipe segment used for estimating the fluid viscosity. The physical model scale factor was 1524 relative to the model cell considered in the computational model.

Proper use of such a large-scale model depends on developing flow through the model at a Reynolds number (Re) matching that occurring in actual plant vessels. Typically, a fluid with considerably higher viscosity than water is utilized, and in the present study, glycerol was used as a flow material. The viscosity of the glycerol is quite sensitive to temperature and to the presence of small quantities of water in the solution. Thus this important parameter was determined from measurements of velocity and pressure drop along a simple, unobstructed section of pipe based on the Hagen–Poiseuille relation (Nobel, 1991):

\[
\eta = \frac{\pi D^4 \Delta P}{128 \rho Q L}
\]

where \(\eta\) is viscosity (Pa s), \(D\) is the pipe diameter (m), \(P\) is pressure (Pa), \(Q\) is the volume flow rate \((\text{m}^3 \text{s}^{-1})\), and \(L\) is the length (m) over which pressure is measured.

The volume flow rate of fluid through the model was determined by placing a container at the outlet of the model resting on an electronic balance, giving mass flow over a measured time interval. Mass was converted to volume by dividing by the fluid density \((1258 \text{ kg m}^{-3})\) as determined from the mass of a known volume of glycerol. For pressure measurements, fittings in the pipe were connected to a differential pressure transducer (Dwyer Instruments model 606–3; 0–750 Pa range). This device was also used for measuring pressure drops across the simple pipe section for calculation of fluid viscosity.

**Results**

**Pressures from the computational model**

Pressure declined steadily along the model cell near the inlet and outlet. The influence of the plate, apparent from
Fig. 3. Fluid pressure for points in a plane lying along the vessel axis and perpendicular to the bars of the perforation plate (a plane formed by the model x and y axes; see Fig. 1). The color scale shows a range of pressures from 0 (blue) to 12 Pa (red).

large changes in pressure, extended for only a short distance on either side (Fig. 3). As expected, pressure was constant across the model (y-direction) near the inlet and outlet, but also in regions fairly close to the perforation plate. The pressure drop through the pores near the cell wall was lower than the pressure drop through the more central pores.

The pressure gradient in the model for regions before and after the plate (−26.1 kPa m⁻¹) was about the same as expected for an ideal pipe of equivalent diameter. However, the pressure gradient within the pores was about 40-fold greater than that calculated away from the plate (−1207 kPa m⁻¹; Fig. 4). Considering a 150 μm long distance around the plate, the total pressure drop was 9.56 Pa, and 3.25 Pa (34%) of this drop occurred along a 2.7 μm distance centred on the pore (twice the depth of the pore). These considerations would suggest that the perforation plate is indeed a highly significant source of resistance to water flow along vessels. However, the computational model does not consider the full length of each vessel member, but only the regions near the plate. Assuming that vessel members in this species are 727 mm in length, there would be an additional 577 mm added to the model before another plate would be encountered. These considerations were described earlier for equation (1) to be used in calculating an overall plate effect of 23.2% for this model.

Tests of the computational model

The model was tested through a process of refining the finite element mesh, particularly around the pores in the perforation plate (Table 1). Preliminary models of a simple cell, but without a perforation plate, showed that elements of the dimensions used in the ‘low’ model were adequate to provide computational solutions that matched the analytical solution for a simple pipe (Hagen–Poiseuille equation; Nobel, 1991) within less than 1% (data not shown). Thus the refinements to the model were focused on regions near the perforation plate.

The initial decrease in the size of elements in a direction along the axis of the cell (x-direction) produced a 20% decrease in pressure drop through the cell (Table 2; low

Fig. 4. Fluid pressure along the centre of the modelled vessel with a perforation plate (highy model). The location of the pore along this path is indicated by the two dotted lines whose spacing reflects the distance through the pore (1.31 μm).
Flow through perforation plates

Table 1. Model structure, including the total numbers (n) of elements in the model and the sizes of elements in the regions away from the plate (Cell elements) and within the pores of the plate (Pore elements)

<table>
<thead>
<tr>
<th>Model</th>
<th>Elements</th>
<th>Cell elements (µm)</th>
<th>Pore elements*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n</td>
<td>Depth</td>
<td>Width</td>
</tr>
<tr>
<td>Low</td>
<td>112 235</td>
<td>2.83</td>
<td></td>
</tr>
<tr>
<td>Medx</td>
<td>166 037</td>
<td>1.89</td>
<td></td>
</tr>
<tr>
<td>Gradx</td>
<td>134 995</td>
<td>1.89 (2.83)</td>
<td></td>
</tr>
<tr>
<td>Medy</td>
<td>148 091</td>
<td>1.89 (2.83)</td>
<td></td>
</tr>
<tr>
<td>Medporex</td>
<td>148 986</td>
<td>1.89 (2.83)</td>
<td></td>
</tr>
<tr>
<td>Highy</td>
<td>236 610</td>
<td>1.89 (2.83)</td>
<td></td>
</tr>
<tr>
<td>Hiyhix</td>
<td>236 610</td>
<td>1.62 (3.25)</td>
<td></td>
</tr>
</tbody>
</table>

*Data are for Pore 10; length, 21.79 µm; width, 4.85 µm; depth, 1.31 µm.

Table 2. Pressures near the inlet (x=0) and outlet (x=150) for the various models tested

<table>
<thead>
<tr>
<th>Model</th>
<th>Mean (\nu) (Pa m(^{-1}))</th>
<th>(P_{x=0}) (Pa)</th>
<th>(P_{x=150}) (Pa)</th>
<th>(\Delta P) (Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>26 865</td>
<td>17.494</td>
<td>1.1862</td>
<td>16.308</td>
</tr>
<tr>
<td>Medx</td>
<td>26 685</td>
<td>14.231</td>
<td>1.1693</td>
<td>13.062</td>
</tr>
<tr>
<td>Gradx</td>
<td>26 685</td>
<td>14.356</td>
<td>1.1766</td>
<td>13.179</td>
</tr>
<tr>
<td>Medy</td>
<td>26 762</td>
<td>12.424</td>
<td>1.1898</td>
<td>11.234</td>
</tr>
<tr>
<td>Medporex</td>
<td>26 708</td>
<td>12.294</td>
<td>1.1902</td>
<td>11.104</td>
</tr>
<tr>
<td>Highy</td>
<td>26 762</td>
<td>10.722</td>
<td>1.1658</td>
<td>9.556</td>
</tr>
<tr>
<td>Hiyhix</td>
<td>26 713</td>
<td>10.226</td>
<td>1.1681</td>
<td>9.058</td>
</tr>
</tbody>
</table>

*Pressure gradient at inlet and outlet (away from perforation plate).

versus medx models). However, a model with elements that grade from large at the model ends to small near the plate showed a similar decrease in pressure drop, indicating that the element size near the perforation plate was important. Subsequent models were designed with smaller elements within the pores of the perforation plate. Because these elements in the pores are projected outward to the inlet and outlet to form the complete model, changes in the pore elements also reflect upon the elements before and after the perforation plate. Increasing the number of elements across the pores from 2 to 3 (gradx to medy models) resulted in a 15% decrease in pressure drop (Table 2). Increasing the number of elements in the depth of the pores from 2 to 3 (medy to medporex models) resulted in an additional 1% decrease in pressure drop. A further reduction in pore element size by increasing the number of elements across the pores from 3 to 4 and along the pores from 12 to 18 (medporex to highy model) resulted in a 14% decrease in pressure drop (Table 2). One additional model (hiyhix) was created without increasing the total number of elements in the model by increasing the size of elements away from the plate in order to make smaller elements near the plate (Table 1). This reduction of element size near the plate (hiyhix model) produced an additional 5% decline in model pressure drop. All of these model refinements ultimately resulted in reductions in the volume of the finite elements and produced changes in the model solution. A comparison of model pressure drop and element volume suggests pressure drop decreased linearly with element volume (Fig. 5). The highy model solution was used for presentation of results because it represented the finest overall construction—although the elements in the hiyhix model were slightly smaller near the plate, elements away from the plate were larger than in any other model tested.

Flow velocities from the computational model

The paraboloidal inlet boundary condition (peak velocity of 1.0 mm s\(^{-1}\)) was recovered a short distance beyond the perforation plate (Fig. 6). The peak velocity at the reference point in the outlet (\(x=150\) µm) is slightly lower than at the inlet reference point (0.9639 and 0.9854 mm s\(^{-1}\), respectively), but a numerical integration of the outlet curve yields an area within 1% of the area.

Fig. 5. Pressure drop between the inlet and outlet reference points (\(x=0\) and \(x=150\)) for models with finite elements of various volumes. The line between the data points was determined by linear regression, giving a slope of 2.821 and an intercept of 7.673 (correlation coefficient of 0.997).
of 38.1 mm diameter \( (D) \) can be calculated from:

\[
\frac{dP}{dQ} = \frac{128\eta L}{\pi D^4}
\]

where \( P \) is the pressure \((\text{Pa})\), \( Q \) is the volume flow rate \((\text{m}^3\text{s}^{-1})\), \( L \) is the length \((\text{m})\) of the section over which pressure is measured, and \( \eta \) is the dynamic viscosity \((\text{measured as 0.828 Pa s})\). For the present model, the slope of the pressure–flow relationship was 20.72 Pa cm\(^{-3}\) and the predicted slope for a model without the plate was 16.01 Pa cm\(^{-3}\). Pressure differences in the model were measured across a 1 m length, while at this scale the actual cell would be 1.108 m in length—thus an additional 1.73 Pa cm\(^{-3}\) must be included. Combining these values in a manner illustrated by equation (1) gives a plate effect of 21.0%.

**Discussion**

From the modelling results reported here, about one-quarter of the resistance encountered by water flowing along the vessels of *Liquidambar styraciflua* could be attributed to the perforation plate. Although the pores are potentially a source of high resistance because of their narrowness, they are very short (in the flow direction) and the perforation plates of individual vessel elements making up the vessel are widely spaced relative to their length. These characteristics appear to reduce the significance of the plate as a source of resistance.
Flow through perforation plates

Fig. 8. Fluid velocity vectors for points in a plane lying along the vessel axis and perpendicular to the bars of the perforation plate (a plane formed by the model x and y axes; see Fig. 1). The entire model and all 20 pores are not shown, but only a region including the central four pores. The color scale shows a range of flow speeds from 0 (blue) to 1.0 mm s$^{-1}$ (red).

A number of physical models of perforation plates were developed by Ellerby and Ennos (1998) in a study of perforation plate effects on flow resistance. Models with 5, 7 or 12 bars in plates oriented at angles from 15° to 90° produced resistance increases ranging from 1% to 19% relative to vessels without a plate. Plates at angles similar to those considered here had resistance increases of about 4%, but these plates had only 12 bars, the modelled cells were somewhat wider (30 μm as opposed to 25 μm, here), and their plates did not have rims around the plate that were incorporated into the present study. Thus the specific construction of models might account for differences between the results of Ellerby and Ennos (1998) and those reported here.

Several computational models were developed in the present study with differences in the size of the elements used to construct the model. A comparison of computational model pressure drop and element volume suggests...
that further reductions in element size would produce only small changes in the solution. The apparent linearity of the relationship between finite element volume and pressure drop might suggest that one extend this relationship to infinitely small elements and use the intercept of this line for calculating pressure drop. If one calculates a plate effect based on the intercept of the linear expression noted in Fig. 5, the pressure drop of 7.67 Pa would give a plate effect of 16%. Such a calculation would assume that the relationship continues to be linear beyond the data shown and there are reasons for suspecting that this may not be true. Typically, the solution of a numerical model might be expected eventually to approach a true solution asymptotically and thus one might not be justified in a linear extrapolation.

Reductions in element size and the accompanying increase in the number of elements in the model began to produce models with large storage and computation time needs. For example, the high model required 6.1 gigabytes of temporary storage and 22 d of processor time, whereas the other versions had more modest requirements (1–2 gigabytes of storage and 3–5 d processing). In comparing computational and physical flow models, Ellerby and Ennos (1998) felt that computational models had inherent weaknesses because the finite element mesh could only approximate the true vessel. It is suggested that all models, whether physical or computational, are approximations of reality and hence both approaches can be useful for providing insight concerning fluid flow systems.

In comparison with the perforation plates of *Liriodendron tulipifera* having fewer but larger pores, the 20 pore plates modelled here play a greater role in the resistance to water flow through vessels. Although more pores would increase hydraulic conducting ability, to a first approximation this increase might be linear with number of pores (conductances in parallel add), while the conductance of narrower pores would decrease with pore size to the fourth power (as in the Hagen–Poiseuille relation; Nobel, 1991). An increase in the number of pores might reduce the effect of the plate, but if those pores were necessarily narrower, the reduction in pore size might be of greater significance. Thus an increasing contribution by perforation plates with greater numbers of narrower pores has some theoretical justification.

Engineers often speak of a need for several hydraulic diameters of distance along a conduit following a change in diameter for the development of the paraboloidal profile characteristic of laminar flow. However, this distance depends on the Reynolds number, and for very low Reynolds flow (as present in these vessels), a paraboloidal flow pattern (termed fully developed flow) might be expected to reappear a short distance after the perforation plate. For example, if fluid enters a circular conduit with constant velocity across the inlet, one can consider a dimensionless entrance length as the distance from the inlet to the point where the flow becomes fully developed divided by the conduit diameter. A typical entrance length is equal to 0.06 Re (Munson et al., 1990), however, for slow viscous flow, White (1991) describes the entrance length as \( 0.6/(1 + 0.035Re) + 0.06Re \), thus as Re approaches zero, the entrance length may not approach zero, but a value of 0.6. It is important to note that the pressure drop where the flow profile is developing is greater than that occurring once the flow is fully developed. These considerations suggest that the distance travelled by fluid within the pore is an important component of the plate, in addition to the width and height of the pores.

The nature of the perforation plate—a large number of pores spread out over a plate at a low angle relative to the vessel axis—reduces its significance as a source of resistance. For the modelled plate, the total pore area was 1412 \( \mu m^2 \) compared to the cross-sectional area of the vessel member, 491 \( \mu m^2 \). In addition, the pores are fairly short in the flow direction. Thus the characteristics of the plate, particularly orientation, act to reduce its effect. Results from the models developed here also indicate that the influence of the perforation plate on fluid velocity and pressure is surprisingly localized; in approaching the strongly inclined plate, fluid does not seem to be affected by the plate even as the inlet vessel member becomes narrower until very close to the pores. These considerations might allow one to model more complicated plates by considering only short distances before and after the plate.

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References


