

MODELLING OF JET IMPINGEMENT IN TWIN-WIRE PAPER-MACHINES: IMPINGEMENT ON ONE FABRIC

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ABSTRACT

Important paper qualities like the formation, fines distribution and two-sidedness are influenced by the geometry of the forming section of a twin-wire paper machine. To be able to control these qualities, it is crucial to have a good understanding of the flow behaviour in the forming zone. In the past, there has been a focus on the roll and blade drainage, but the jet impingement zone may also significantly influence these qualities.

We have studied the fluid dynamics of jet impingement in a roll-former. The computational fluid dynamics (CFD) software FLUENT was used to develop a two-dimensional model that predicts pressure distribution, shear and flow velocities in the jet impingement zone. The VOF (Volume of Fluid) method was used to predict the shape of the pulp suspension jet, and the forming fabrics were represented as permeable media obeying Darcy's law with an extra inertial term. These equations also model the fibre mat resistance when fibre-mat build-up is included in the simulation.

Preliminary results for jet impingement on a single wire were obtained for typical values of fabric resistance, impingement angle, and jet velocities used in paper machines for printing grades. The influence of fabric rush/drag was also studied. The results show that the drainage force from jet impingement is important only in the vicinity of the impingement point. Approximately 50% of the drainage takes place over a distance comparable in size to the jet thickness. Higher jet velocities lead to slightly higher drainage values. The pressure distribution is mainly influenced around the impingement point and not further downstream. Lower impingement angles lead to less drainage. For the cases of both varying jet velocity or impingement angle, the computed values follow the predicted trend from a simple one-dimensional model. In the case of varying rush/drag, shear stresses are nearly constant downstream of the impingement location. The influence of fibre-mat build-up on drainage was computed by including an average drainage resistance for the fibre-mat.

INTRODUCTION

In recent years, several studies of twin-wire forming sections have been conducted. The intent of these studies is to understand the influence of machine settings on drainage characteristics and paper qualities like the formation, fines distribution and two-sidedness. Such studies have been carried out on blade forming ([1], [2], [3]) as well as on roll forming ([4], [5], [6]). The jet impingement zone may also have a significant influence on paper properties, but studies of this drainage zone are rare.

Audenis in 1999 [1] developed a theoretical model for jet impingement of an inviscid jet of water on a single permeable wire. He used a fixed domain numerical method in his computations and predicted the jet shape and velocity distribution. The theoretical model improved a former model by using a permeable medium condition, but with the permeable medium condition considered only high impingement angles and assumed 100% drainage (achieved by applying suction) within the modelled domain. The 100% drainage is necessary as it is not possible in this model for fluid to flow out of the sides of the domain, all water has to leave the domain through the fabric. In contrast, jet impingement angles in roll-formers are about 10° or less, and only a small part of the drainage takes place at jet impingement.

Johnson [8] measured pressure and drainage profiles for jet impingement on a Bel Baie II with preferential impingement on the conveying wire. He showed the dependence of drainage on the distance between the impingement point and first deflector. Jong [9] did analytical and experimental studies of the characteristics of jet impingement in order to find the effects of operating parameters on flow and mat properties and also on sheet formation. In 1998, Chen et al. [5] extended a previous one-dimensional model of forming in a crescent former to a two-dimensional viscous model, with the two dimensions being MD and CD. However, although the domain they examine extended from the free jet to the end of the forming roll and therefore includes the jet impingement zone, they did not specifically look into jet impingement. Osterberg [10] related pressure and velocity in the initial part of a twin-wire former to a fabric resistance number he proposed. He included only the inertial part of the flow (neglecting viscosity) and neglected fibre-mat build-up as well as the curvature of the fabrics. Gune et al. [11] did an experimental study on a very simplified case of jet impingement in narrow channels formed by two counter-rotating rolls. They observed flow reversal as a result of an adverse pressure gradient for solid rolls with no drainage. They related the adverse pressure gradient to jet speed, jet/wire speed ratio and gap geometry.

The objective of our work was to develop a two-dimensional viscous fluid flow model for the jet impingement zone to overcome some of the restrictions of the previous models. As a first step, jet impingement on a single wire was investigated. The results are presented in this paper.

MODEL SETUP

The problem of modelling jet impingement is quite complex. It involves free surfaces, stock which is a non-Newtonian fluid, a permeable wire, a fibre mat with varying drainage resistance formed on the fabric, and a complex geometry. To minimize some of these difficulties, jet impingement on a single straight wire was modelled. This is a good starting point for modelling the twin-wire geometry, and furthermore can be used to predict jet impingement on a

Fourdrinier. Also, it is relevant to jet impingement in twin-wire machines if the jet impinges preferentially on the conveying wire, as is often the case.

The following assumptions were made to further simplify the problem:

- The fibre suspension is very dilute and therefore can be modelled as pure water (Newtonian fluid)
- The consistency of the suspension remains unchanged during drainage (fibre-mat build-up as a filtration process rather than a thickening process)
- Laminar flow is assumed
- The velocity profile of the incoming jet is constant over the height of the jet (negligible boundary layer thickness exiting the headbox)
- The fabric remains straight in the impingement zone (wire tension $\rightarrow \infty$)

To solve for the flow, the Navier-Stokes-equations in conjunction with a free surface model called a VOF (Volume of Fluid) method were used. This adjusts fluid properties in each cell according to the volume fraction of the different fluids in that cell, in our case water and the surrounding air. The interface between the air-water (which here presents the jet surface) is tracked with the help of the continuity equation. Details of the VOF model are described in [12] as well as in [13].

The FLUENT code was used to solve the equations. By default, convergence in this code is normally assumed to occur when the sum of the residuals falls below 10^{-3} . However, because of problems with numerical diffusion at the interfaces, the residual for pressure in this problem did not fall below 10^{-2} . Therefore, the convergence criterion was not based on the residual sum. Rather the solution was assumed to be converged when there was a levelling out of the residuals when plotted as a function of the number of iterations. Convergence then was verified by checking mass continuity for the problem. If the difference between incoming and outgoing mass fluxes was less than 0.5% or smaller the solution could be assumed to be converged.

The computational domain was a simple rectangle with one side representing the fabric, as shown in **Figure 1**. The fabric is defined as a porous medium with an adjacent pressure boundary. The incoming jet is defined as an inflow boundary condition, where the magnitude and direction of the inflow velocity as well as the volume fraction are defined (volume fraction of water = 1). The other boundaries can be simply defined as static pressure boundaries with zero static pressure and a volume fraction of water of 0. The volume fraction is calculated from upstream flow conditions as long as the flow exits the domain at the respective boundary and therefore the definition of volume fraction as air or water at these boundaries does not matter. Two of the boundaries (at the top and above the incoming jet) are defined as slip-wall boundaries instead of pressure boundaries. This was done to improve convergence; the solution for the impinging jet was not influenced by this modification.

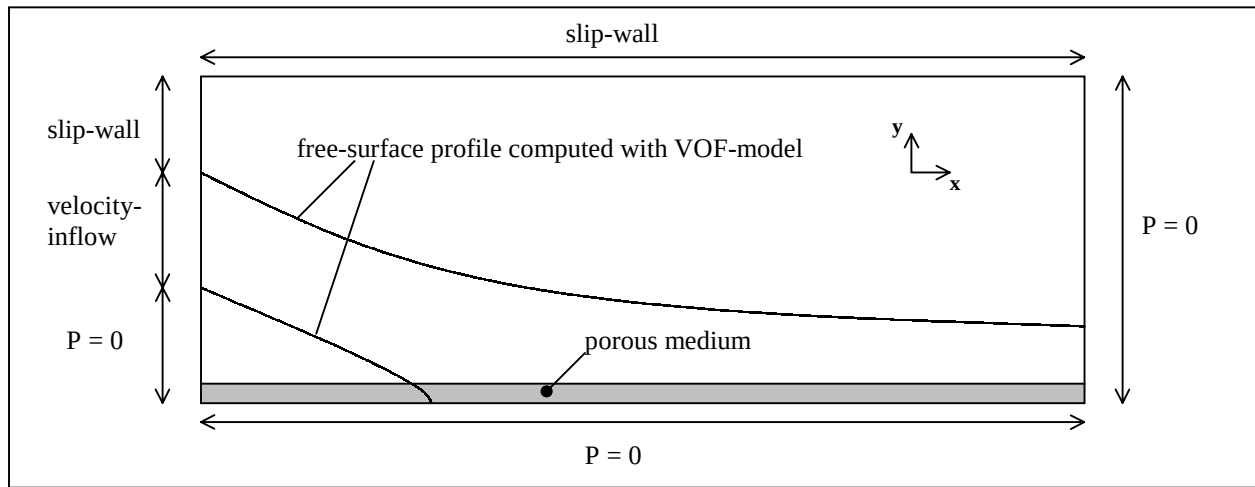


Figure 1. Model setup and computed free surface.

The length of the modelled domain was 10 cm and the height was 3 cm. A structured mesh covered the domain. Due to problems with numerical diffusion, a very fine mesh with 400 x 200 cells was used unless stated otherwise, with the cells spaced closer in the y-direction, normal to the fabric. In the x-direction the cells were distributed evenly. In the y-direction, they were unevenly distributed, with more cells concentrated near the fabric.

For the computations, a jet-thickness of 10 mm was always used along with a fabric thickness of 1 mm. Other variables like jet and fabric speed, impingement angle and fabric resistance were varied throughout the study and therefore are described in the respective sections.

One problem in modelling jet impingement is that the fabric characteristics have to be known. The resistance depends on the fabric type. The different values for fabric descriptions given in **Table 1** could be found in the literature. In some cases the fabric resistance is described as a combined inertial and viscous resistance ([14], [15]), whereas others use only an inertial resistance [16]. For two cases, where inertial and viscous resistance are both given, computations were done by using either only inertial resistance (sets 1a) and 3 a)) or using inertial and viscous resistance (sets 1 b) and 3 b)). For set 2 only an inertial resistance was given for the fabric (case 2 a)). Cases 1 to 3 c) include an additional resistance when fibre-mat build-up is included.

	Set 1 a)	Set 1 b)	Set 1 c)	Set 2 a)	Set 2 c)	Set 3 a)	Set 3 b)	Set 3 c)
C_2 [m ⁻¹]	$3.37 \cdot 10^4$	$3.37 \cdot 10^4$	$3.37 \cdot 10^4$	$6 \cdot 10^4$	$6 \cdot 10^4$	$1.9 \cdot 10^5$	$1.9 \cdot 10^5$	$1.9 \cdot 10^5$
α [m ²]	∞	$1.27 \cdot 10^{-10}$	$8.36 \cdot 10^{-11}$	∞	$4 \cdot 10^{-8}$	∞	$8 \cdot 10^{-11}$	$2.35 \cdot 10^{-11}$

Table 1. Inertial and viscous resistance factors used in the computations.

The description the code uses for porous medium description is a Darcy-Law type equation with an additional inertial resistance:

$$\Delta P = \frac{\mu}{\alpha} \cdot v \cdot \Delta n + \frac{1}{2} \cdot \rho \cdot C_2 \cdot v^2 \cdot \Delta n$$

μ	viscosity of fluid [Ns/m ²]
α	viscous resistance coefficient [m ²]
ρ	density of fluid [kg/m ³]
C_2	inertial resistance coefficient [m ⁻¹]
v	fluid velocity [m/s]
Δn	thickness of porous medium [m]

The resistance coefficients are defined separately for each phase as well as for the different directions. For the computations, it was assumed that the fabric offers no resistance towards air ($C_2 \rightarrow 0$, $\alpha \rightarrow \infty$), and it was assumed that water can flow only perpendicularly to the fabric plane through the fabric. The resistance in the fabric direction (not the through-fabric direction) for water therefore was infinite.

VALIDATION OF THE VOF MODEL

Jet Impingement on an Impermeable Wall

To verify the applicability of the VOF model to this specific problem, computations were done for jet impingement on a straight, impermeable slip-wall. The Reynolds-Number of this problem is $5 \cdot 10^6$ at a velocity of 15 m/s, which shows that inertial forces will be high, the use of potential flow theory for comparison is reasonable and the results should show good agreement.

Figure 2 shows the contours of the computed pressure-distribution and the computed shape of the impinging jet for an impingement angle of 10° and a jet velocity of 15 m/s. **Figure 3** shows the computed and theoretical pressure distribution along the impingement wall for impingement angles of 30° and 10° at 15 m/s jet velocity.

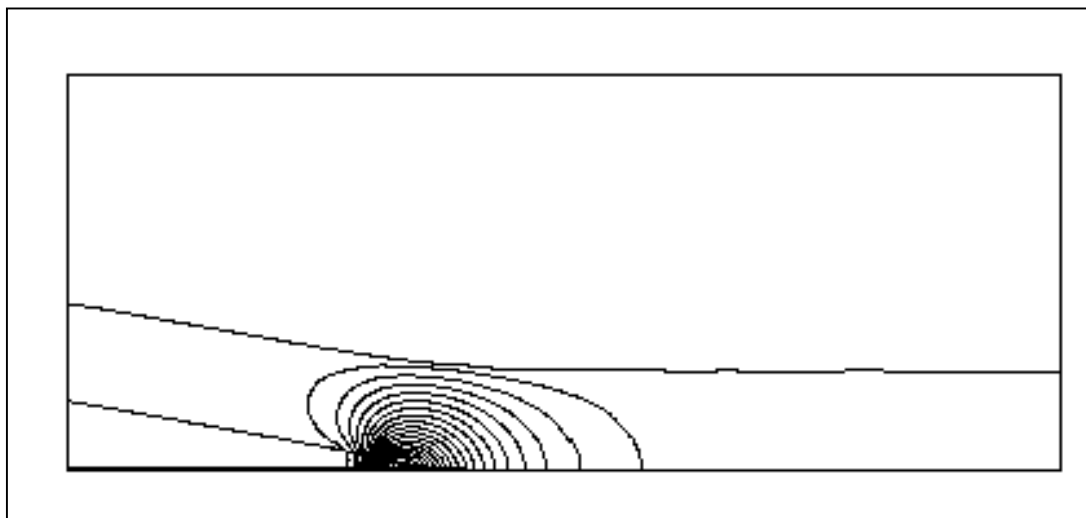


Figure 2. Sample computation of jet impingement onto a solid surface: Free surface and pressure contours (jet velocity 15 m/s, impingement angle 10°).

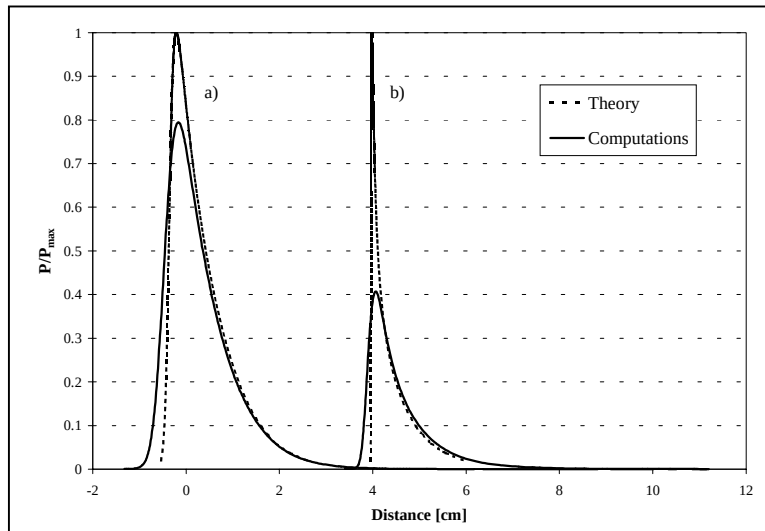


Figure 3. Comparison of the viscous computer code and the inviscid potential flow theory of the pressures developed during impingement of a jet onto a solid surface for a) $\theta = 30^\circ$ (300 x 46 cells) and b) $\theta = 10^\circ$ (400 x 160 cells).

One can see that the overall pressure distributions match very well. However, the peak pressure is predicted very poorly, especially at lower impingement angles. This poor prediction of peak pressure is caused by numerical diffusion, which occurs at the interface between the air and water. The prediction of peak pressure can be improved by using finer meshes and better solution procedures, but computation time goes up. At lower angles, it was not possible to obtain mesh-converged solutions for peak pressure, due to limitations in the mesh size which can be used in the software. Therefore, at least for lower angles, the prediction of the peak pressure will not be accurate. On the other hand, the integrated pressure along the wall agrees very well between computation and theory: For different meshes and solution methods, the integrated pressure was overpredicted in the computation compared to the theoretical values by 3 to 8% at an impingement angle of 10° . Keeping in mind that we are comparing a viscous code with an inviscid theory, these predictions are fairly accurate. The good agreement, despite the poor prediction of peak pressure, can be explained by the fact that the peak pressure occurs only over a very small distance (in the order of 1 mm for $\alpha = 10^\circ$) and the pressure gradient at the impingement point is very high. The peak pressure therefore has only little influence on the overall integrated pressure.

MESH-CONVERGENCE FOR JET IMPINGEMENT ON A MOVING PERMEABLE FABRIC

When looking at jet impingement on a moving permeable wire, another factor affecting the accuracy of computed results comes into play. Depending on the fabric resistance, the interface between water and air needs some time to penetrate the fabric after impingement. In practice, this can be seen as a separation between the location of impingement and where water first comes through the wire. In the computations this penetration time causes some complications, as the question of mesh-convergence becomes more important than in the case of jet impingement on an impermeable wall. As long as the interface between air and water is located in the fabric,

the values for fluid properties will be influenced by the remaining air, which in turn influences the calculation of pressure drop over the thickness of the fabric.

Computations for different sets of fabric resistances, listed in Table 1, in combination with different mesh-sizes were done. Jet impingement angle in all cases is 10° and jet velocity is 15 m/s as before. **Figure 4** shows the calculated drainage amounts as a function of mesh-size. While for most sets the values differ only with the range of uncertainty of the calculations, it can be seen that for sets 1 b) and 1 c) mesh convergence was reached only for the two finer meshes. However, when looking at the pressure distributions for these sets with different meshes, for example for set 1 b) (**Figure 5**), only slight differences in the pressure distribution can be detected. Equal differences were found in the plots for those sets, where mesh-convergence was given for all three meshes. Therefore, one has to be careful when judging mesh-convergence. Also, the pressure distributions in the early part of jet impingement when the interface between the two phases has not yet penetrated through the fabric, have to be looked at with caution.

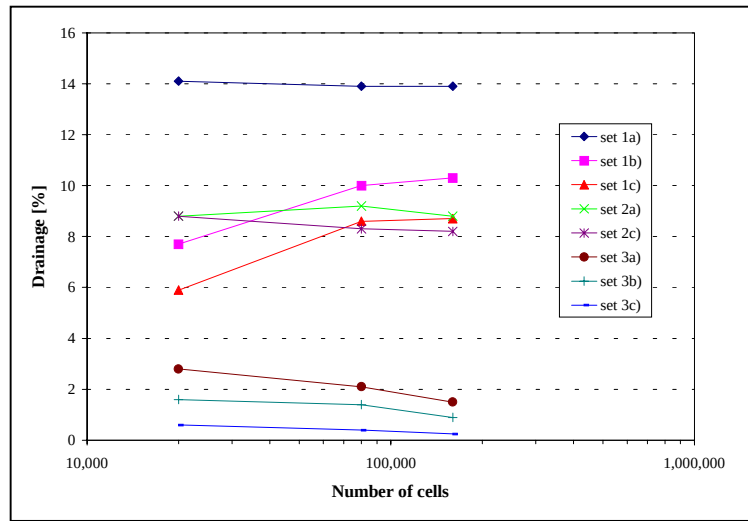


Figure 4. *The effect of mesh-size on predicted drainage through the fabric at impingement. Cases with 20,000 cells were done on a 200x100 mesh, cases with 80,000 cells used a 400x200 mesh, and cases with 160,000 cells used a 400x400 mesh.*

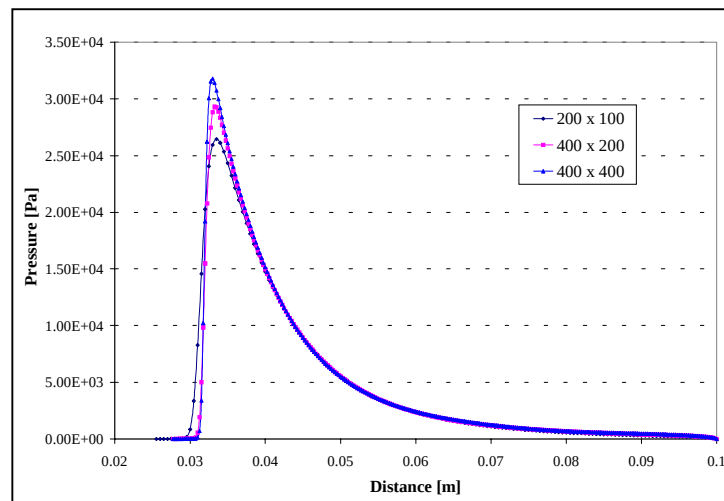


Figure 5. *The effect of mesh-size on predicted pressure at the fabric during impingement (using set 1 b) for fabric resistance description).*

From Figure 4 it can be seen that mesh-convergence seems to be more critical in cases where viscous forces are more of influence (higher viscous resistances combined with lower inertial resistances). The proposed mesh-size of 400 x 200 cells seems sufficient for the given conditions and therefore will be used in the computations. However, when certain variables are changed, mesh-convergence should be checked again. (Lower impingement angles, lower jet-velocities, and higher fabric resistances, especially viscous, are particularly problematic.)

Overall it was concluded that the VOF model can be used to model jet impingement, as long as the integrated pressure and drainage amounts are of interest and not the peak pressure.

Although the issues of mesh-convergence and numerical diffusion seem to be somewhat restraining, it has to be kept in mind that the ultimate goal of this work is to establish a model for twin-wire forming. In twin-wire forming, penetration of suspension through the fabrics will be much faster due to the higher pressures developed and free surfaces occur only before the fabric wedge comes together. Therefore, the above mentioned problems will be of much less influence in the case of jet impingement in twin-wire machines.

FABRIC RESISTANCE: INFLUENCE OF INERTIAL AND VISCOUS FORCES

It is interesting to examine the influence of inertial and viscous forces at jet impingement, knowing that in many studies it is assumed that viscous forces at impingement are negligible. Therefore, a comparison of pressure distribution at the fabric was done for the fabric resistances of sets 1 and 3 a) and b), which gave a distinction between inertial and viscous resistance.

The values for drainage resistance of fabrics found in the literature (Table 1) are quite different. From Figure 4 it can be seen that drainage through the fabric depends very much on the resistance of the fabric. Adding a viscous resistance influences the drainage amount noticeably, especially if the inertial resistance is in the lower range (set 1 a), b)). However, comparison of the pressure distribution at the fabric (**Figure 6**), shows little difference between the computations for inertial resistance only and the ones for both inertial and viscous resistance. Furthermore, when comparing the pressure profile of set 1 a) or b) with the one of set 3 a) or b), the curves differ only close to the impingement point, where a prediction is difficult due to the problems with numerical diffusion. Further from the impingement point, where the results are not influenced by the interface and therefore are assumed to be accurate, the pressure profiles of sets 1 and 3 nearly overlap. This is unexpected, as drainage for these sets was very different. An explanation might be that different fabric resistances will influence the pressure distribution only close to the impingement point, but further downstream the free surface accommodates for different fabric resistances. An alternative explanation is that for all cases 85% or more of the water is not drained, and the small amount that is drained does not substantially affect the pressure distribution.

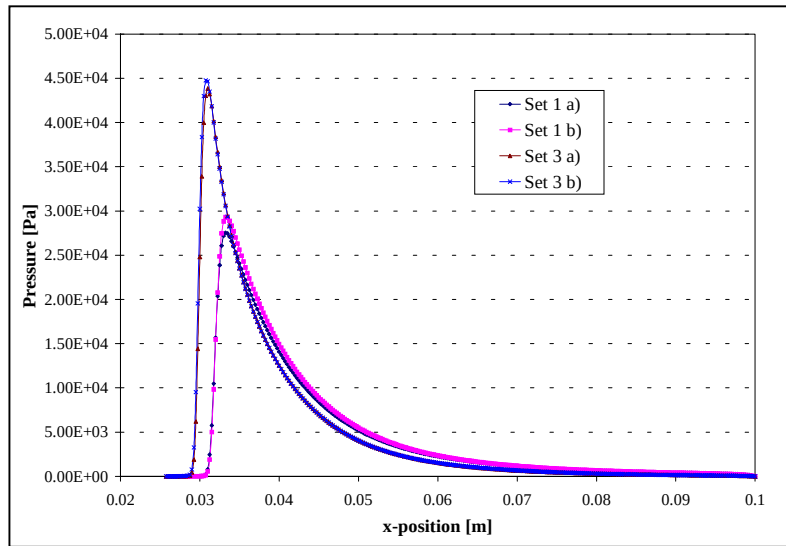


Figure 6. *Pressure profiles at fabric: Fabric resistance given by inertial resistance only or by combined inertial/viscous resistance.*

INFLUENCE OF JET VELOCITY

In order to investigate the influence of jet velocity, computations for jet velocities ranging from 15 m/s (900 m/min) to 25 m/s (1500 m/min) were done. The impingement angle was set at 10° for these computations. The velocity of the fabric in each case was the same as the jet velocity. Fabric resistance of set 1 b) was used for these computations. This resistance includes inertial and viscous terms and gave reasonably high drainage amounts. The computations were done for a jet of water only, neglecting the fibre-mat build-up.

Figure 7 shows a comparison of the pressure profiles along the fabric. As expected, the pressure is higher and the curve also somewhat broader for higher jet-velocities. The pressure pulse is significant only over the first 2 to 3 cm after impingement.

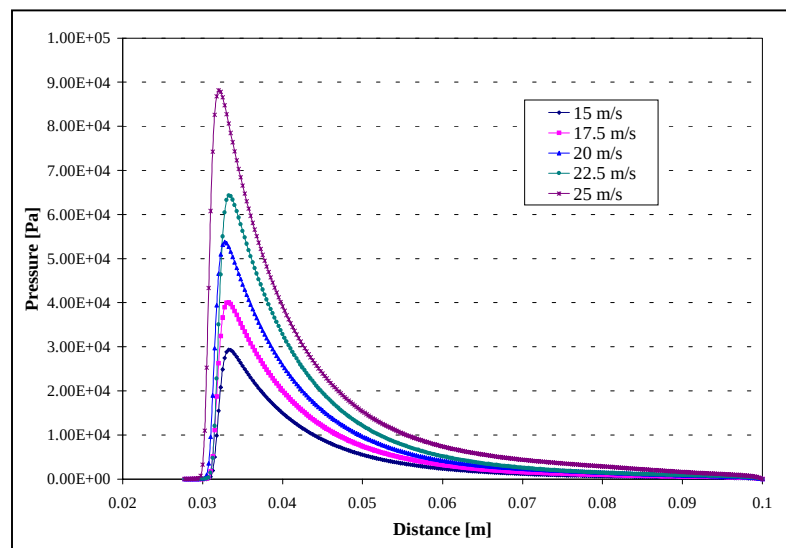


Figure 7. *Influence of jet velocity on the computed pressure profiles at the fabric.*

Figure 8 shows the integrated pressure as a function of jet velocity. The computed integrated pressure was compared to a simple one-dimensional analysis. Neglecting drainage, the momentum equation in this case can be used to calculate the force on the fabric (for one metre machine width) as

$$F = \int p dx = \rho h v_{jet}^2 \sin \alpha$$

The comparison shows that the computed values as a function of jet velocity follow the same trend as the results from the one-dimensional analysis, but are about 10% lower. This seems reasonable, as with drainage the force on the fabric should be lower than without. **Figure 9** gives the drainage amounts (absolute and as a fraction of inflow), also as a function of jet velocity. The drainage amounts include the water which actually drains from the fabric plus the water remaining in the fabric, assuming 60% void fraction of the wire. To obtain these numbers, a correction of the computed values was done, as the porous medium model of the software assumes a 100% void fraction. The relative drainage amount as a fraction of incoming flow remains constant even at different jet-velocities. For the given variables the relative drainage amount is about 15%.

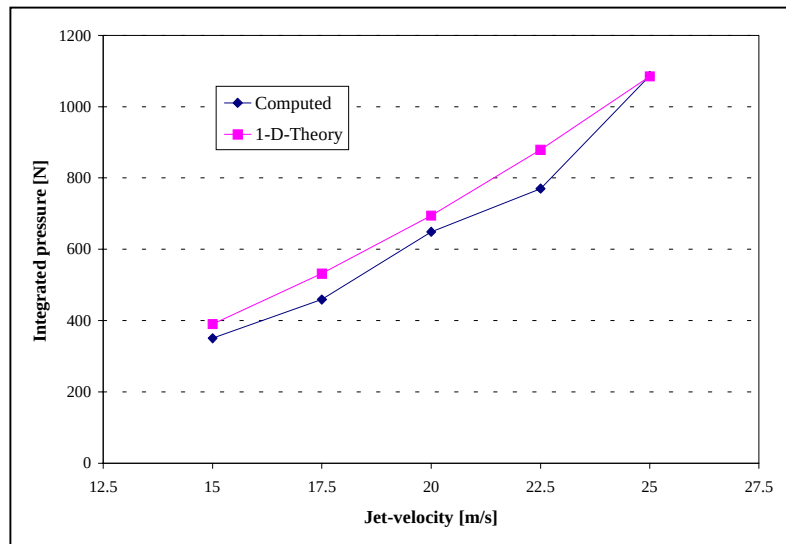


Figure 8. *Computed integrated pressure at the fabric as a function of jet velocity and comparison with a simple one-dimensional analysis.*

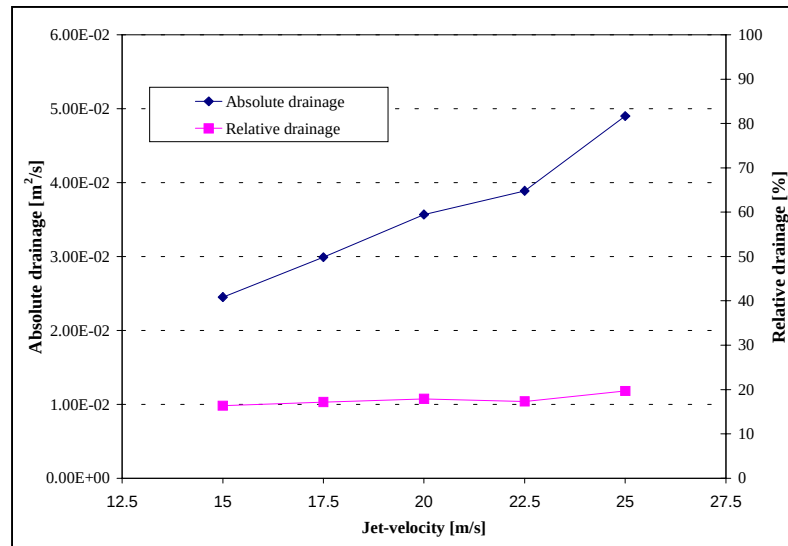


Figure 9. Computed drainage as a function of jet velocity (given in absolute values per metre of machine width and as a fraction of the incoming flow volume).

Another interesting aspect is to look at the distance over which the majority of drainage occurs at impingement. The drainage velocity profiles along the fabric (y-component of the velocity) for different jet-velocities are shown in **Figure 10**.

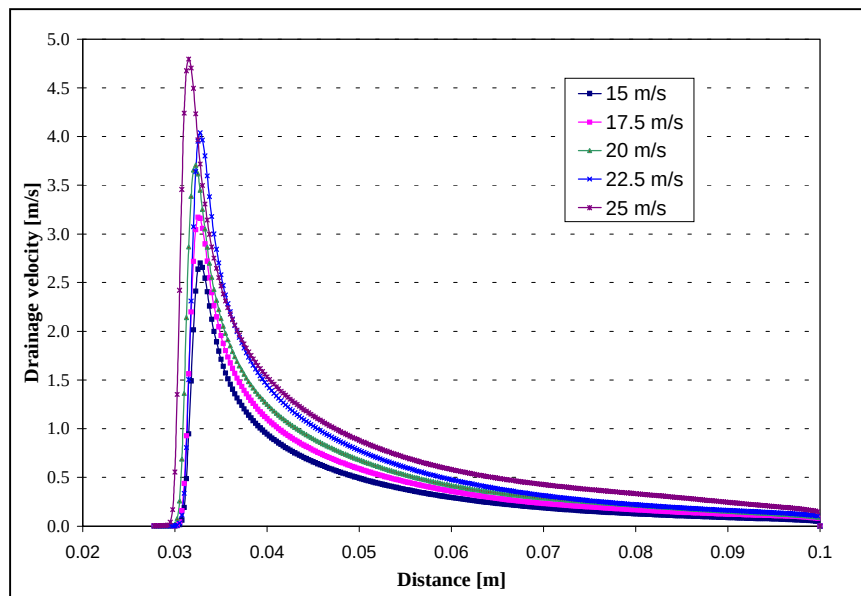


Figure 10. Influence of jet velocity on drainage velocity through the fabric.

From the drainage velocity profile it is possible to calculate the fraction of drainage which was completed over a certain distance. **Table 2** shows the fraction of the overall drainage achieved during impingement at certain distances after jet impingement. Independent of jet velocity, nearly 50% of the drainage is completed after only one centimetre. After that the drainage rate falls rapidly so that an additional 20% is drained in the second centimetre and after 4 cm drainage is between 85 and 90% complete. It can be concluded that the influence of jet

impingement is significant only over a very small distance; one-half of the drainage occurs within a distance comparable to the jet-height.

jet velocity [m/s]	drainage after 1 cm [%]	drainage after 2 cm [%]	drainage after 4 cm [%]
15	49	70	90
17.5	48	69	88
20	47	68	87
22.5	48	68	88
25	44	64	85

Table 2. Fraction of drainage completed after distances of 1 cm, 2 cm and 4 cm for different jet-velocities.

INFLUENCE OF IMPINGEMENT ANGLE

Computations were done for various impingement angles while keeping the other variables constant. Impingement angles of 4°, 6°, 8° and 10° were used. The jet velocity was 15 m/s and the fabric resistance was described by set 1b) from Table 1. Computations were done considering a jet of water only, with mat build-up neglected.

Figure 11 shows the pressure profiles along the fabric for different impingement angles. The pressure profiles do have similar shapes with a steep gradient at the impingement point and the maximum pressure at about the same location, but are lower in magnitude for lower impingement angles. For an impingement angle of 4°, the pressure gradient at the impingement point is less than for the other angles. As there is no physical reason why an impingement angle of 4° should show a different behaviour from the other angles, this different behaviour is likely due to inaccuracy of the computation at very low angles, and therefore shows the limitations of the model. It should be possible to achieve a better result with a finer computational mesh, but in this case using a finer mesh did not produce satisfactory convergence.

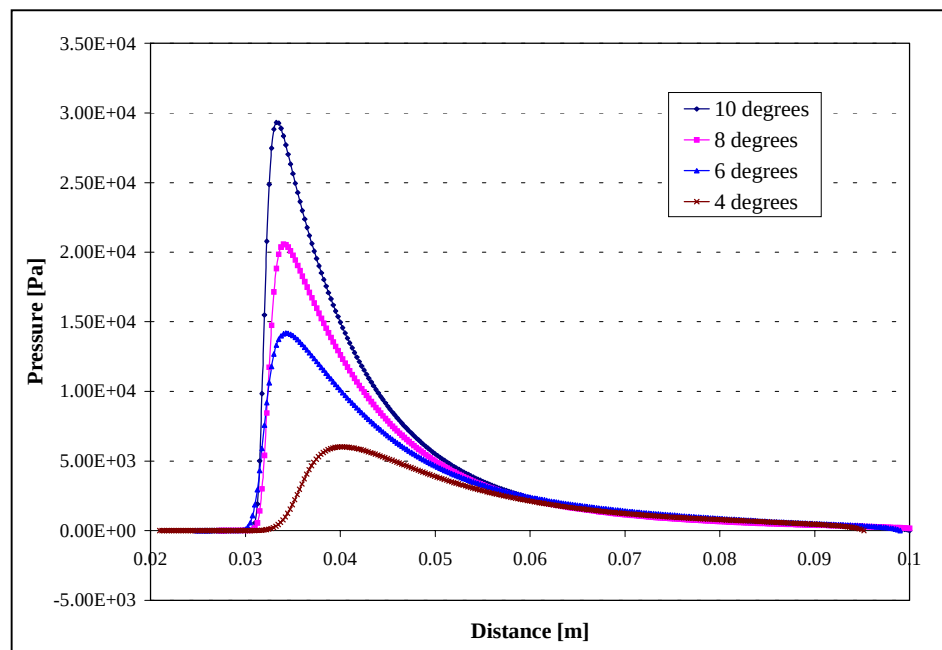


Figure 11. Influence of impingement angle on the computed pressure profiles at the fabric.

Figure 12 shows the computed integrated pressure along the fabric and **Figure 13** the drainage amounts (absolute and as a fraction of inflow), both as function of impingement angle. As expected the integrated pressure is higher with higher impingement angles and so is the drainage (absolute and relative). In both cases the dependence seems to be approximately linear. The integrated pressure was again compared to the one-dimensional analysis. According to the analysis, the integrated pressure should depend on the sine of the impingement angle, which at these low angles is approximately linear. The computed values are again on average around 10% lower, consistent with the fact that the forming fabric is not the impermeable medium assumed in the 1D-analysis.

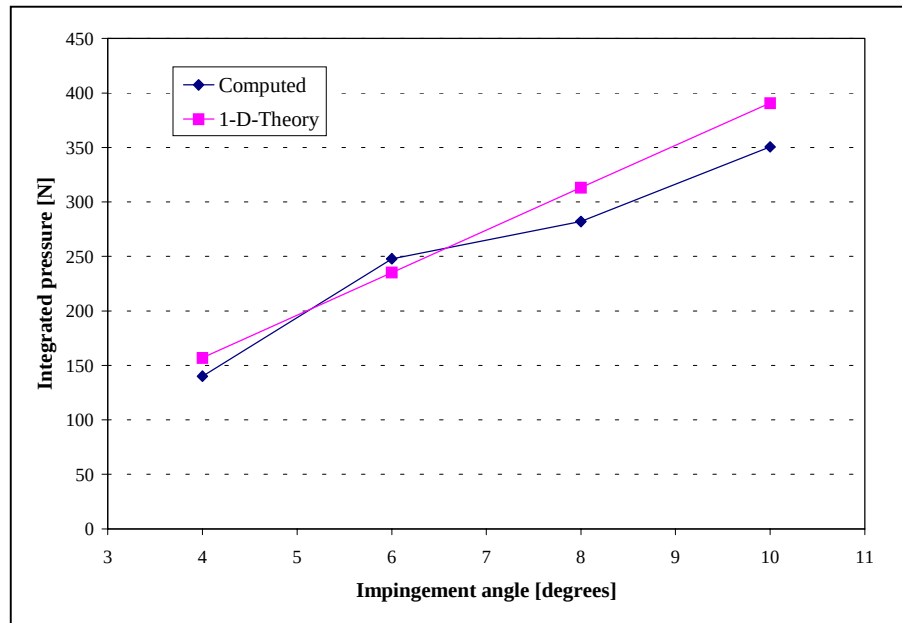


Figure 12. Computed integrated pressure at the fabric as a function of impingement angle and comparison with a simple one-dimensional analysis.

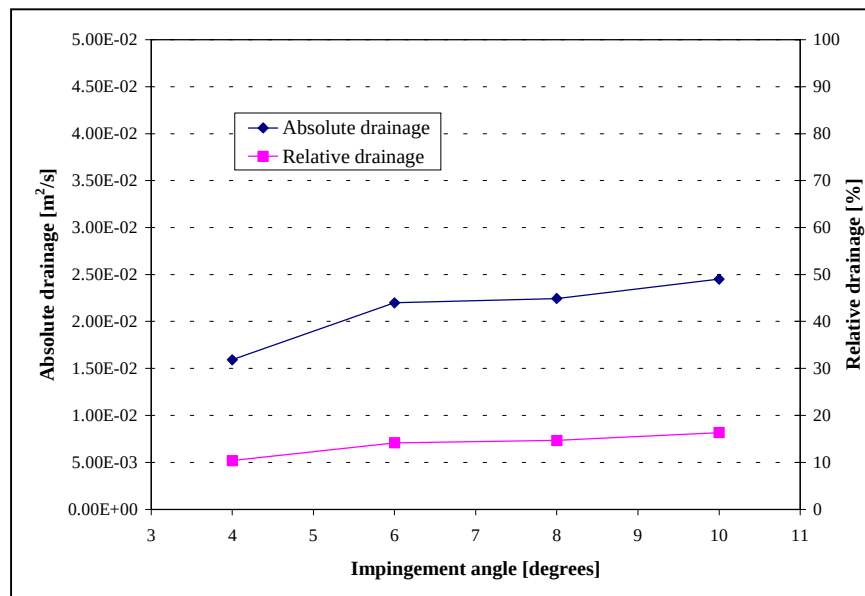


Figure 13. Computed drainage as a function of impingement angle (given in absolute values per [m] machine width and as a fraction of the incoming flow volume).

Drainage velocity profiles were computed (shown in **Figure 14**) and the drainage completed after certain distances as a function of overall drainage was calculated (see **Table 3**). The drainage velocity profiles again look very similar in shape; they nearly overlap further away from the jet impingement point and differ only in magnitude over the first centimetre after impingement. The curve for an angle of 4° shows a much lower slope near impingement than the other angles, which is most likely caused by the truncation error of the computations. From the values for completed fraction of drainage after the first and second centimetre, it can be concluded that with a lower angle of impingement, the fraction of completed drainage over a certain distance is slightly diminished. The fraction of drainage after one centimetre drops from approximately 50% for 10° to 42% at 4° and after two centimetres 70% of drainage are completed at 10° compared to 65% at 4°. At a distance further downstream the fraction of completed drainage is about the same for all angles with approximately 90% at 4 cm. Even at lower angles, therefore, drainage occurs mainly over the first 2 cm after impingement.

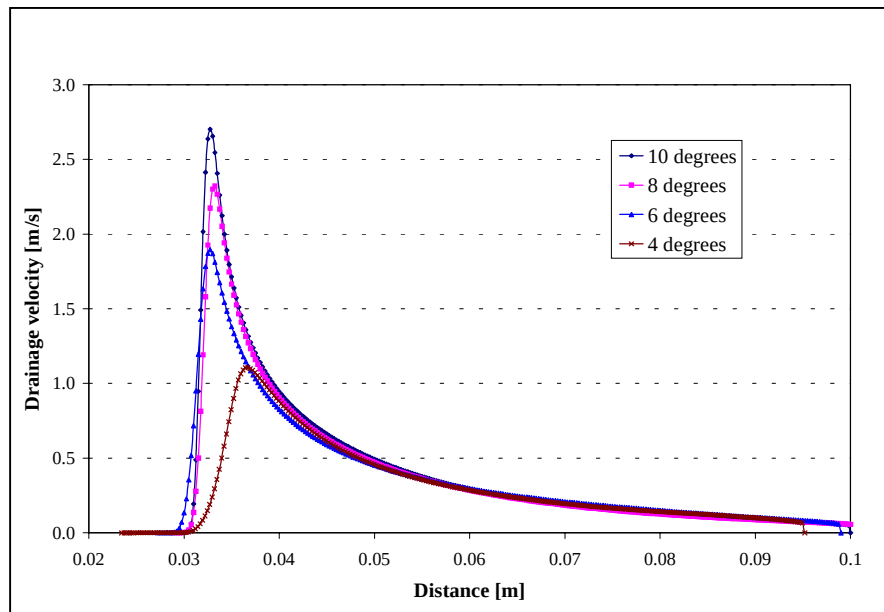


Figure 14. Influence of impingement angle on drainage velocity through the fabric.

impingement angle [°]	drainage after 1 cm [%]	drainage after 2 cm [%]	drainage after 4 cm [%]
10	49	70	90
8	48	69	89
6	45	68	87
4	42	65	88

Table 3. Fraction of drainage completed after distances of 1 cm, 2 cm and 4 cm for different impingement angles.

INFLUENCE OF RUSH/DRAW

The influence of rush/draw on jet impingement was investigated. Computations were done for jet-velocities of 15 m/s (900 m/min) combined with different fabric velocities. Drag ($v_{jet} < v_{fabric}$) was set to 20 m/min, 40 m/min and 60 m/min and rush ($v_{jet} > v_{fabric}$) to 10 m/min. The impingement angle was 10° and set 1 b) was used to describe the fabric resistance. Mat build-up was neglected.

The pressure profiles along the fabric for all cases were very similar, with only slight differences close to the impingement point. As the jet has no information about the fabric velocity except through a very thin boundary layer, this result was expected. The integrated pressure and drainage amounts, given in **Figure 15**, consequently also remain approximately constant for different cases of rush/draw.

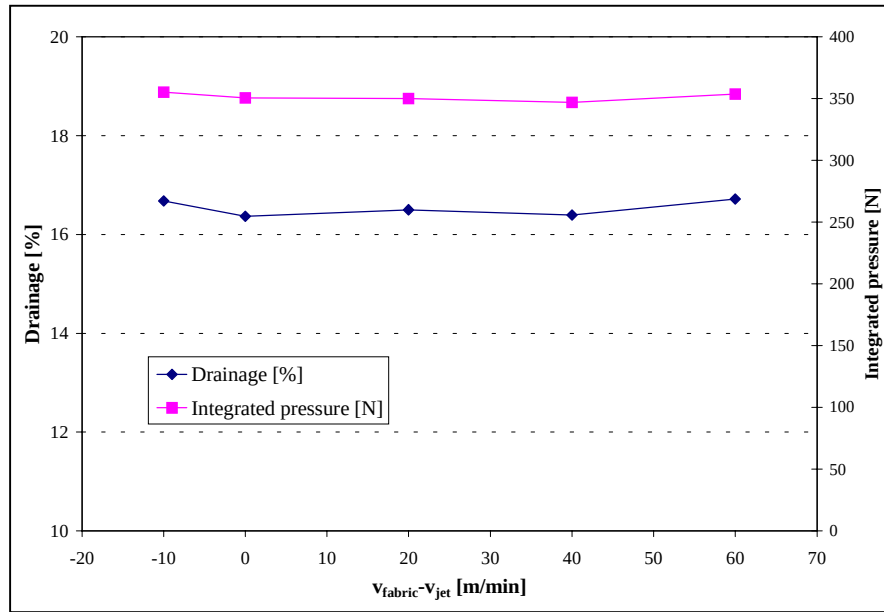


Figure 15. Computed integrated pressure at the fabric and drainage as a function of rush/draw.

When looking at the influence of rush/draw, it is also important to look at the velocity profiles over the height of the jet or at the shear stress at the fabric. The x-component of velocity fell in all cases rapidly from the velocity of the fabric to the velocity of the jet (over the distance of the first two cells, which equals a distance of 0.2 mm) and was then relatively constant over the remaining height of the jet. Only in the case of no rush/draw did the velocity of the jet equal the velocity of the fabric at the end of the computed domain. For the three computed cases of drag the jet was slowly accelerated by the fabric, but a difference in jet and fabric velocity remains at the end of the domain. In the case of 10 m/min rush, the jet velocity was lower than the fabric velocity around the impingement point, but further downstream the jet velocity was higher, which can be seen in the negative values for shear stress along the fabric in **Figure 16**. The shear stress at the fabric could be calculated as

$$\tau = \mu \cdot \frac{u(fabric) - u(jet)}{\Delta y}$$

where the difference in u-velocity was taken over the two cells next to the fabric and thus $\Delta y = 0.2$ mm. This distance presented in all cases the thickness of the boundary layer in this problem, further inwards the average jet-velocity was reached. From Figure 16 it can be seen that the shear was higher with a bigger difference between jet and fabric velocity, as would be expected. At the jet impingement point the shear stress is relatively high due to the deceleration of the jet at impingement, but diminishes quickly and remains relatively constant further downstream.

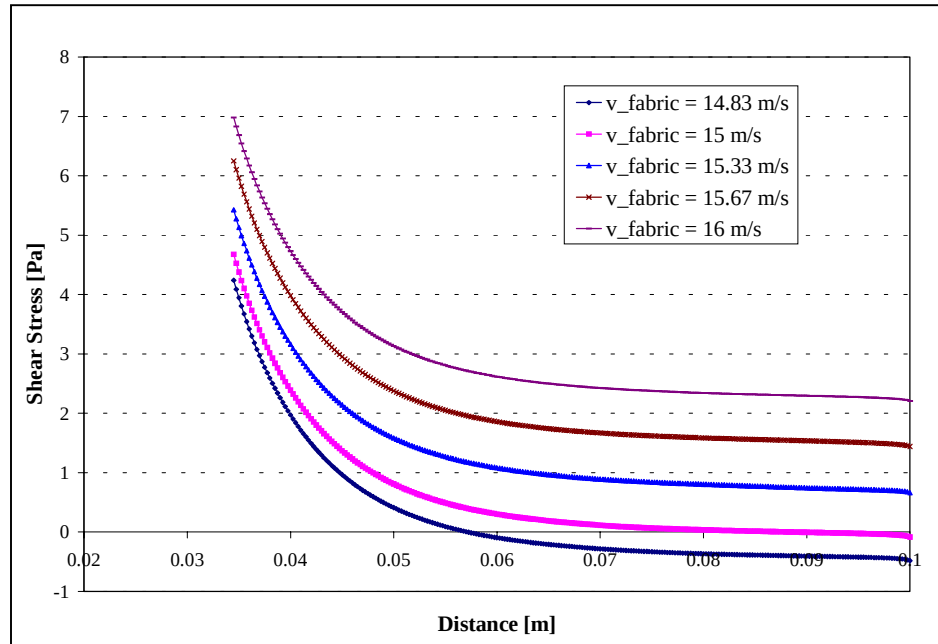


Figure 16. *Shear stress along the fabric for various cases of rush/drag. From top to bottom, the different curves represent decreasing amounts of drag (jet velocity was 15 m/s).*

COMPUTING FIBRE-MAT BUILD-UP

When computing jet impingement for different jet velocities, impingement angles and rush or drag of the fabric, the fibre-mat build-up was always neglected. Although the fibre-mat which is deposited over the first centimetres after impingement will be very thin, it will still have an influence on the overall filtration resistance. Therefore some preliminary computations were done including the effect of fibre-mat build-up.

However, to be able to include the effect of fibre-mat build-up accurately, it would be necessary to have information about the fibre-mat resistance as a function of deposited basis weight. The measurement of fibre-mat resistance at low basis weight is very difficult and not done very often. In most investigations mat resistance is measured only for basis weights > 10 to 20 g/m^2 . Even when resistance is measured for lower basis weights, the data do not describe resistance reliably as a function of basis weight. For this reason, we decided to start computing fibre-mat build-up by using an average mat resistance value independent of basis weight.

We assumed a final basis weight of the paper of 50 g/m^2 . From Figure 4 it is apparent that the drainage at impingement was always less than 15%, which would equal a deposited basis weight of 7.5 g/m^2 or less. For the computations, the average fibre-mat resistance was then taken as that for a basis weight of 5 g/m^2 and mat resistances were estimated from the literature sources used

before. These sources gave quite different values of the mat resistance, which may be a result of the different furnishes studied or of measurement errors.

The resistance for the fibre-mat was then included in the resistance for the fabric, leading to sets 1, 2 and 3 c) of Table 1. By including fibre-mat resistance in the fabric resistance, the thickness of the deposited fibre-mat is neglected in the geometrical set-up of the model.

A comparison between pressure profiles along the fabric for cases where fibre-mat build-up was either neglected or included showed nearly overlapping pressure profiles. As before, when comparing the different descriptions for fabric resistance, the additional viscous resistance from the fibre-mat does not influence the pressure distribution except very close to the impingement point, where the uncertainty in the data is great anyway. Drainage amounts into the fabric are given in **Table 4**. From the drainage amounts, the deposited fibre-mat after impingement can be calculated as 6.5 g/m^2 for set 1 c) of drainage resistance, 6.3 g/m^2 for set 2 c) and 2.1 g/m^2 for set 3 c). As expected, drainage amounts are slightly less with the fibre mat than without it.

drainage resistance set	drainage without fibre-mat [%]	drainage with fibre-mat [%]
1 b) and c)	14.4	12.9
2 a) and c)	13.6	12.6
3 b) and c)	5.4	4.1

Table 4. Drainage amounts for different sets of drainage resistance a) when neglecting the fibre-mat b) when including the effect of fibre-mat build-up.

A better method to include fibre-mat build-up would consider the resistance as a function of deposited basis weight, if this data would be available. An initial guess of deposited fibre-mat as a function of distance could be calculated from the model without including the fibre-mat. Then a resistance profile for the mat could be calculated and added into the model. The new computation would lead to a different profile of deposited fibre-mat, and thus a different profile for the resistance. With this iterative process the fibre-mat build-up could accurately be computed.

CONCLUSIONS

We have developed a two-dimensional viscous model for jet impingement in twin-wire paper machines. Preliminary results for jet impingement on a single wire are shown. Reasonable results for drainage, pressure profiles and velocity profiles were predicted. The majority of drainage occurs over a distance comparable to the jet thickness. Further downstream, jet impingement forces are of less influence and pressure and drainage profiles along the fabric are not significantly influenced by different variable settings. The model shows that drainage is higher with higher jet velocity and higher impingement angles. The integrated pressure follows the predictions from a simplified one-dimensional analysis. The shear stress along the fabric for different rush/drag of the fabric was computed and found to be large at impingement and nearly constant (at values according to the jet-fabric speed difference) some distance downstream from jet impingement.

The model so far is able to predict flow characteristics for jet impingement on a single wire and therefore can be used to predict jet impingement in Fourdrinier machines. It also gives a very good start for modelling jet impingement in twin-wire formers, where only the modelled geometry has to be changed. Some problems of the models lie in the influence of numerical diffusion at the free jet surface, in particular at low impingement angles. It is expected that this problem will be of even less significance when modelling twin-wire forming, where higher pressures lead to faster drainage of the air-water interface.

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