Inkjet Printing on Textiles: Software Package for Textile Designers

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Abstract

Digitally applying droplets onto the substrate enables new ways of finishing textiles. In this method microdroplets launched from ink-jet printing head are used as a transportation media for certain functional species. This technique has many advantages in comparison with traditional textile finishing methods like bath treatment. Precise control of the species distribution in the substrate enables development of new functional textiles, for expensive functional species it may give large cost saving, however one of most important can be reduction of waste production in manufacturing process. To gain all these advantages textile engineer needs to find optimal printing parameters to obtain desired ink distribution in the textile. Complex nonlinear effects of ink penetration into the textile (mainly capillary phenomenon) make this task very time consuming and may require significant number of expensive preprints. To overcome these difficulties CIM-mes Projekt (within the EU DIGITEX Project) developed a numerical model of ink penetration into the textile and encapsulated it in a form of toolbox for ***Fun****ctional* ***Te****xtile* ***A****rchitecture (****FunTeA CAD****). This paper shows capabilities of developed software on two virtual test cases: development of single sided hydrophobic textile and textile with anisotropic conductive pattern.*

Introduction

In many engineering fields when a product design requires advanced analysis of complicated physical phenomena Computer Aided Design became a routine technique. Nowadays it is impossible to design car or airplane using only experimental data. Computer methods make the design process faster and cheaper. Although digital finishing of textiles is becoming a common technique in industrial printing it is difficult to find a software or even numerical model that can simulate this process. Droplet release and formation from ink-jet printing head together with droplet penetration into flat isotropic substrates e.g. paper substrate is a well recognized subject. Unfortunately textile is highly anisotropic with capillaries forming complex three dimensional structure. These special features of textile substrate requires special treatment and shows that development of numerical model which can predict final ink distribution for certain printing parameters is needed. In literature only few papers can be found with analysis of ink-jet printing on textiles. Paper by Bidoki et al [3] shows promising experimental results of printing conductive patterns on textiles. Liou et al in [5] obtained very good agreement of numerical simulation and experiments in printing on microcavities. Neyval et al in [6] developed a numerical model for droplet penetration into porous surface and performed validation with experiment. This examples show that it is be possible to simulate printing on textiles, but unfortunately it is difficult to find papers describing numerical simulation of this process. This paper will try to fill this gap. Presented results are a part of research performed for past few years, intermediate results where already published in [1] and [2].

Physical phenomena

Ink-jet printing is a method for transporting certain species onto the substrate. Droplet formation and release from the nozzle is a complex fluid mechanics problem including surface tension (increasing surface tension at increasing expansion rate of water-air interface), contact phenomenon and in some cases even non-Newtonian fluid (decreasing viscosity at increasing shear rate). Droplet released from the nozzle after flying about 1mm distance with speed of about 8m/s is hitting the substrate. In the first milliseconds kinetic energy of droplet is dissipated by viscosity and flow is starting to be dominated by capillary effects. Although finding the equilibrium of such process for flat plate is an easy task, complicated substrate geometries make it much more difficult to solve. Final droplet configuration strongly depends on intermediate stages of the process therefore simulation must be unsteady. Another challenge is proper construction of the textile geometry which has not only complex fiber configuration, but also random dimensions which can strongly affect the final droplet trace. Droplets may also interact between each other in higher printing resolutions which may significantly affect the final species distribution in textile. Another problem comes with species diffusion inside droplet and into the fibers during penetration. Depending on diffusion constant and surface reaction rate species may be equally distributed on wetted textile surface or the concentration may be non-uniform. As it was outlined printing and droplet penetration process is very complex, however it is possible to create a numerical model under certain modeling generalization, therefore the question is what quality of information this model can provide and is it sufficient for textile engineers.

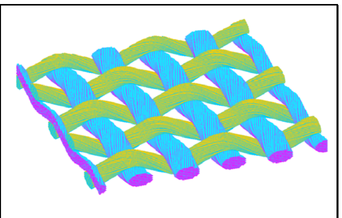
Figure 1. Open and closed plain-woven fabric and a closed 3-1 twill fabric.

Textile construction

Droplet deposition onto textile fabrics is hard to describe, because of the highly anisotropic structure of the yarns in the weaving pattern and of the fibers in the yarn. A geometrical model of fabrics is to be presented in this paper, which lead to a construction (weaving pattern) of yarns made up of specified fibers. A set of parameters is used to make a unique construction of any type of fabric 1. The geometrical fabric model is based on 3 principles: (1) no overlap of neighboring fibers, (2) fitting yarn crossings, (3) use of appropriate boundary conditions of the weaving construction at the yarn crossings. Fabric construction basically consists of yarns, built up of a bundle of parallel fibers, and associated with 3 properties: twisted, compressed and bent 2. Compression leads to ellipsoidal shaped yarn and fiber sections. Fabric weaving structure basically depends on a warp bending factor (range 01). It defines the relative force balance in the fabric construction due to the curvature of the yarns at the crossings in the weaving structure (Fig. 3. Warp bending factor also leads to extra yarn length in warp and weft direction. The set of parameters that is used to make a unique fabric construction comprises 5 terms for the warp and weft yarns: yarns/10cm, yarn count, yarn composition, yarn twist and extra yarn length. The fabric twill structure is the last parameter that uniquely defines the fabric construction. Yarn composition defines yarn density and the average density and thickness of its constituent fibers. An open plain-woven fabric (Fig. 1, left) can be constructed according to the parameters given in table 1). The warp bending factor, as well as the compression of warp and weft yarns (indicated in bold in table 1), is chosen in order to satisfy the conditions of extra length for that yarns.

Table 1. Construction of an open plain-woven fabric.

	Warp	Weft
Yarns/10cm	244	230
Yarn count	38	38
Composition	100% PES	100% PES
Yarn twist	600	600
Twist direction	Z	Z
Yarn length	102%	106%
Compression	1.38	1.39
At crossing	1.38	1.39
Fibers/yarn	118	118
Fabric twill	1-1	
Twill direction	-	
Warp bending	0.393	



A closed plain-woven fabric (Fig. 1, center) can be constructed, besides with the parameters in table 2, with the extra conditions that yarn expansion is limited in the narrow spacing between the yarns at the crossings. Yarn compression results, in

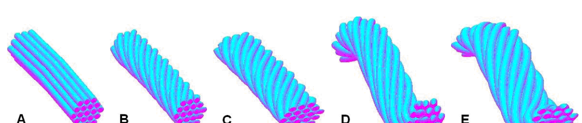


Figure 2. *Sample yarns for fabric construction: (A) with 19 parallel fibers, (B) twisted, (C) twisted + compressed, (D) twisted + bent and (E) twisted + bent + compressed.*

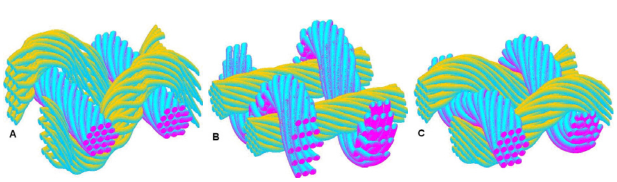


Figure 3. *Sample fabric weaving structures with 3 typical values of warp bending factor: (A) factor = 0.05, (B) factor = 0.95 and (C) factor = 0.5.*

Table 2. Construction of a closed plain-woven fabric.

	Warp	Weft
Yarns/10cm	270	214
Yarn count	10	10
Composition	100% PES	100% PES
Yarn twist	625	625
Twist direction	Z	Z
Yarn length	116%	111%
Compression	1.29	1.44
At crossing	2.25	1.99
Fibers/yarn	268	268
Fabric twill	1-1	
Twill direction	-	
Warp bending	0.605	

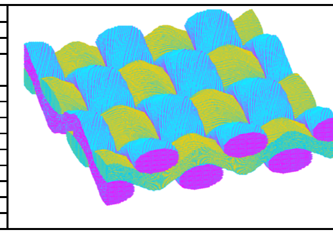
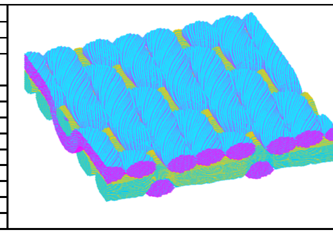


Table 3. Construction of a closed 3-1 twill woven fabric.

	Warp	Weft
Yarns/10cm	458	211
Yarn count	20	12
Composition	100% PES	100% PES
Yarn twist	750	570
Twist direction	Z	Z
Yarn length	107%	108%
Compression	1.31	1.39
At crossing	1.31	2.63
Fibers/yarn	134	223
Fabric twill	3-1	
Twill direction	S	
Warp bending	0.657	



that case, in yarn consolidation. Warp bending factor and yarn compression factors are indicated in bold in table 2. The conditions of extra yarn length are also satisfied. A closed 3-1 twill fabric (Fig. 1, right) has a typical surface, built up with closely packed yarns. It can be constructed according to the parameters given in table 3, but with extra restrictions at the yarn crossings, yielding bent yarns in the horizontal plane of the fabric. See table 3 for the requested warp bending factor and yarn compressions for this fabric. Many fabrics can thus be determined in the way as indicated in tables 1 thru 3, and so giving a "fingerprint" for the use in droplet deposition manifolds of yarn surfaces.

Numerical Model

First step to simulate printing on textiles was to obtain correct results for one droplet penetration into the substrate. This task was performed with CFD-ACE+ solver. Parametric analysis and experimental validation of this approach is described in [2]. Unfortunately simulation of flow for more than few microdroplets with CFD is impossible even with largest computer clusters because of significant difference in length scales which results in very large computational grids. To overcome this difficulty simplified flow solver was created which is using as an input wicking data from CFD single droplet simulations. Model includes effects from complex configuration of capillaries and interaction between droplets. In this approach droplet flow is simulated only in single unit cell of textile (see 6) therefore results can be easily extrapolated onto larger peace of fabric. Input data to the simplified solver can be also provided from experimental preprints for certain textile-ink configurations.

In order to make numerical model accessible by textile engineers graphic user interface was created, where user can define textile and ink parameters, printing pattern and all other relevent input information. Simulation results are obtained after few minutes on typical desktop computer. Results can be observed by final ink distribution in three dimensions and in any textile cross-sections. Surface map of ink penetration depth can be also created which can give good insight into the ink distribution inside the substrate. Numerical model always needs an experimental verification and calibration. Comparison of CFD results for single droplet penetration with printed samples is described in [2]. Large scale verification of results presented in this paper is under development, however initial very promising comparison between simulation and experiment shows fig. 4.

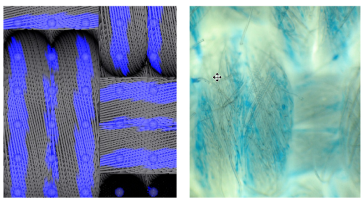


Figure 4. *Comparison of simulation results (left) with experiment (right) for* 180*dpi and* $40pl$ *droplet. Ink parameters: viscosity =* $8cP$*, contact angle =* 30°

Presented software can be also used for parameter analysis of printing on textiles. Figure 5 shows influence of the droplet size for $40pl$ droplets and 180dpi printing resolution. It can be seen that larger droplets give larger surface coverage which is what one can expect, however next section will show that more complicated printing configuration can give not so evident results.

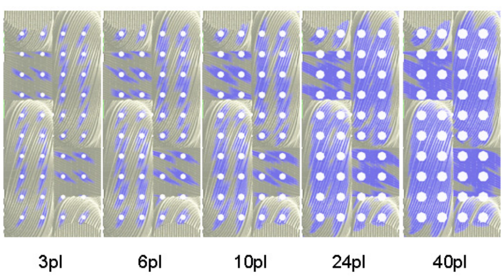


Figure 5. *Simulation for different droplet size for 180dpi, viscosity =* $1cP$*, contact angle = 30*$^\circ$

Testcase

To show the capabilites of ***FunTeA CAD*** (*toolbox for **Fun**ctional **Te**xtile **A**rchitecture*) two virtual testcases are presented. First testcase can be considered as very academic, however it can show that very small modyfications of prinitng pattern can significantly affect the result. Second testcase is closer to application, it shows very clearly the influence of droplet size and printing resolution onto the visible surface coverage of textile.

Conductive Textile

Printed circuits are very important for development of advanced functional textiles. General task of this testcase is to create a functional textile with anisotropic conductance which means that the electric resistance of the textile in one direction will be significantly larger then in another. Initial concept of solving this problem was to print lines with large resolution using conductive ink and assume that droplet traces will overlap each other and form a conductive lines. Numerical results of this approach shows figs. 6. It can be seen that for 360dpi resolution conductance will be very limited due to capillary effects which stretch the droplet trace in the direction almost perpendicular to the printed line.

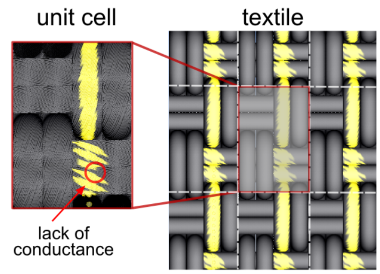


Figure 6. *Analysis performed for single unit cell shows that for* 360*dpi line there will be lack of conductance.*

Simple solution to this problem can by a rotation of the substrate by 34°, in this case alignment of capillaries in the textile agree with the printed line which results in optimal ink distribution in terms of conductance (see fig 7). Fig 7 shows also the penetration depth map which is difficult to obtain with experiment.

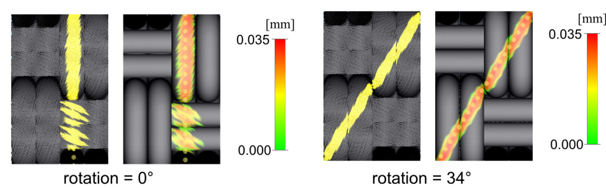


Figure 7. *Rotation of the textile by* 34° *can significantly change the final conductance. Pictures on the left hand side show penetration depth.*

Single Sided Hydrofobicity

Idea of Single Sided Hydrofophic textile is to create a product which will be waterproof and breathable at the same time. Breathability can be obtained with good water vapour transport features which is usually in conflict with keeping textile waterproof. Such problem can be solved by making the textile hydrophobic (large contact angle with water) however this can decrease the vapour transport. To maintain good performance of textile in terms of breathability ink-jet technology is used to cover the textile with special hydrophobic ink only at the outdoor side, which will increase the contact angle only locally. Printing parameters for this process should be chosen very carefully, because uncovered places on textile surface may result in water leak, therefore ***FunTeA CAD*** will be used to determine optimal droplet size and printing resolution.

Figure 8 shows ink penetration for different droplet size and print resolution. It can be seen that for larger droplets and for larger resolutions surface coverage is better. In table 4 visible surface coverage is presented. Depending on the necessary coverage value for certain functionality optimal parameters can be chosen also in terms of ink amount per $1inch^2$. Here even for very small $8pl$ droplets 97.32% of coverage can be obtained with much lover ink volume when compared to $40pl$ cases.

Important parameter especially in terms of washability can be penetration depth. Fig. 8 shows map of penetration depth for different droplet size and print resolution. Penetration depth can

Table 4. Visible surface ink coverage for different droplet size and print resolution.

Volume $[pl]$	Print resolution [dpi]	Ink Volume $[\mu l/inch^2]$	Visible Surface Coverage $[-]$
8	360	1.04	63.71%
8	400	1.28	75.51%
8	540	2.33	91.46%
8	**720**	**4.15**	**97.32%**
24	360	3.11	91.35%
24	400	3.84	94.57%
24	540	7.00	98.35%
24	720	12.44	99.44%
40	360	5.18	95.80%
40	**400**	**6.40**	**97.11%**
40	540	11.66	99.05%
40	720	20.74	99.80%

be also very well observed in cross-sections (fig. 9) and on three dimensional surface map (see fig.10).

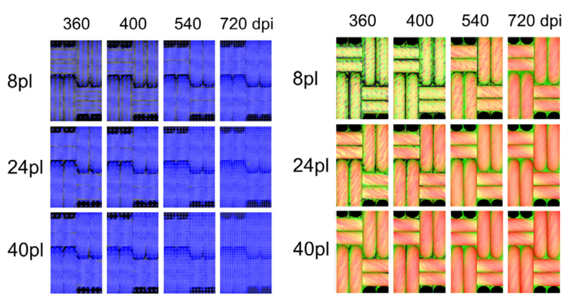


Figure 8. Textile coverage, ink visualisation for different droplet size and print resolution (left) and map of penetration depth (right). Ink parameters: viscosity = $6cP$, contact angle = $30°$

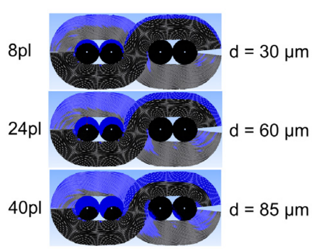


Figure 9. Penetration depth (textile cross-section) for 8, 24 and $40pl$, print resolution = 720dpi, viscoscity = 6cP, contact angle = 30°.

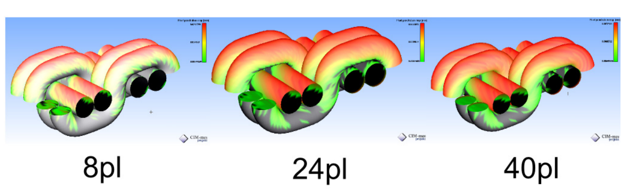


Figure 10. Map of penetration depth for 8, 24 and $40pl$, print resolution = 720dpi, viscoscity = 6cP, contact angle = $30°$. Red color shows deeper penetration.

Conclusions

Presented results show that using modeling tools it is possible do predict ink penetration into the textile. Developed software can be used directly be engineers which can decrease time of product development and decrease cost of experimental work, however extensive experimental validation and calibration is still needed. Some initial experimental data shows good agreement with simulation, but it should be compared with larger experimental data set. Although quantitative prediction of ink penetration can have at least 30% error, the qualitative results show correct tendencies and good prediction of wicking effect, therefore ***FunTeA CAD*** can be already used for development of new functionalities and better understanding of printing on textiles.

Acknowledgments

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Author Biography

Armen Jaworski received his M.Eng from the Warsaw University of Technology in 2006 and now is finishing his Ph.D in adjoint methods for aerodynamics. Since 2007 is working in CIM-mes Projekt on development of numerical models for ink-jet printing on textiles. His aeronautical background mainly on numerical methods and optimization and experience with development of CFD software is giving new insight into complex engineering problems existing in textile industry.

Kees Heil graduated from Eindhoven University of Technology with M.Sc. in 1979 and Ph.D. in 1984. After working in several areas of process technology and fluid engineering in the last two decades, Dr. Heil now has a position as research scientist digital finishing at Xennia Holland BV in Nijverdal, the Netherlands. Backgrounds are fluid dynamics, energy systems, process engineering and nonwovens. Current topics are "characterization of and fluid flow in textile materials" and "advanced printing systems".