
**Test methods for the experimental
characterization of in-plane
permeability of fibrous
reinforcements for liquid composite
moulding**

*Méthodes d'essais pour la caractérisation expérimentale de la
perméabilité dans le plan des renforts fibreux pour le moulage de
composites liquides*

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO document should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

ISO draws attention to the possibility that the implementation of this document may involve the use of (a) patent(s). ISO takes no position concerning the evidence, validity or applicability of any claimed patent rights in respect thereof. As of the date of publication of this document, ISO had not received notice of (a) patent(s) which may be required to implement this document. However, implementers are cautioned that this may not represent the latest information, which may be obtained from the patent database available at www.iso.org/patents. ISO shall not be held responsible for identifying any or all such patent rights.

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For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 61, *Plastics*, Subcommittee SC 13, *Composites and reinforcement fibres*.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

Liquid composite moulding (LCM) processes are employed for the manufacture of fibre reinforced polymer composites (FRPC). In all LCM processes, dry fibrous reinforcements are impregnated with a liquid resin system, which is cured following reinforcement impregnation to form the matrix in which the fibres are embedded. Impregnation is driven by positive applied pressure and/or vacuum. LCM is widely applied for the manufacture of lightweight components in the automotive, aerospace, marine, and energy (e.g. blades for wind turbines) industries.

To obtain short cycle times and high component quality in LCM, i.e. fast and complete saturation of the reinforcement with liquid resin, a suitable process design is required, based on knowledge of material properties. Darcy's law relates the phase-averaged flow velocity to the applied pressure gradient, the dynamic resin viscosity, and the reinforcement permeability for fluid flow. The permeability of fibrous structures, such as reinforcements, is generally direction-dependent and is described by a symmetric second-order tensor. Diagonalisation of the tensor leads to three principal permeabilities, which correspond to the flow oriented along three orthogonal axes, two of which describe the in-plane permeability.

This document focuses on the experimental characterization of unsaturated in-plane permeability of reinforcing materials for LCM. As with any kind of experiment, methodological, systematic and statistical errors may arise. In order to minimize methodological errors caused by different experimental methods, this document covers the two most common approaches, linear and radial flow experiments. Systematic errors inherent to these methods are minimized by distinct procedures for preparing and executing the flow experiments as well as for post-processing the acquired measurement data as prescribed in this document. Statistical errors are dominated by variations in material properties, particularly inhomogeneous areal weight and thus, fibre volume fraction of the reinforcing materials. This document covers well known statistical methods, such as multiple experiments at repetitive conditions, in order to estimate the uncertainty associated with the results.

Test methods for the experimental characterization of in-plane permeability of fibrous reinforcements for liquid composite moulding

1 Scope

This document specifies test methods for the experimental characterization of in-plane permeability of fibrous reinforcements for liquid composite moulding. Requirements for test equipment, test methods and data analysis are detailed, to ensure optimal accuracy and reproducibility of the results.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the cited edition applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 286-1:2010+Cor1:2013, *Geometrical product specifications (GPS) — ISO code system for tolerances on linear sizes — Part 1: Basis of tolerances, deviations and fits*

ISO 2555, *Plastics — Resins in the liquid state or as emulsions or dispersions — Determination of apparent viscosity using a single cylinder type rotational viscometer method*

ISO 21920-2, *Geometrical product specifications (GPS) — Surface texture: Profile — Part 2: Terms, definitions and surface texture parameters*

ISO 21920-3, *Geometrical product specifications (GPS) — Surface texture: Profile — Part 3: Specification operators*

3 Terms, definitions, symbols and abbreviated terms

3.1 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

- ISO Online browsing platform: available at <https://www.iso.org/obp>
- IEC Electropedia: available at <https://www.electropedia.org/>

3.1.1

in-plane permeability

quantitative material parameter of a fibrous reinforcement (a porous medium), relating the phase-averaged flow velocity of a liquid in the reinforcement to the applied pressure gradient and the dynamic viscosity of the fluid.

Note 1 to entry: During impregnation of a fibrous reinforcement with a fluid, the permeability of the fibrous reinforcement, the permeability tensor, $\mathbf{K}$, relates the phase-averaged flow velocity, $\mathbf{v}$, to the applied pressure gradient, ∇p , and the dynamic resin viscosity, μ , as stated in Darcy's law.

$$\mathbf{v} = - \left(\frac{\mathbf{K}}{\mu} \right) \cdot \nabla p$$

As per this definition, the permeability is given in units of square metres (m²). Importantly, the permeability of a reinforcement depends on the fibre volume fraction and the geometrical fibre arrangement. Because of the directionality of the fibre arrangement in a reinforcement, the permeability is generally anisotropic. The principal components of the tensor **K**, in its diagonal form are referred to as k_1 and k_2 , representing the highest and lowest values of the in-plane permeability, respectively.

Note 2 to entry: Permeability is an equivalent parameter defined at the level of an equivalent homogeneous medium representing an intrinsically heterogeneous material. Darcy's law has been extended to unsaturated flow or transient flow, neglecting the effect of dynamic wetting.

3.1.2 unsaturated flow

dynamic flow of a fluid in a porous medium where initially empty (vacuum) pore spaces are filled or an initially present fluid (e.g. air) is displaced

3.1.3 in-plane anisotropy ratio

characteristic of a material showing different properties in different directions

Note 1 to entry: The in-plane anisotropy ratio, α , is defined here as the ratio of lowest to highest in-plane permeability, i.e. $\alpha = \frac{k_2}{k_1}$.

3.1.4 linear injection

injection of fluid into a porous medium along one short edge of a rectangular geometry, resulting in a flow along the long edge, with velocity vectors oriented primarily in one direction

3.1.5 radial injection

injection of fluid into a porous medium through a central injection gate, resulting in a flow with velocity vectors extending radially outward from the gate, in all in-plane directions

3.1.6 race-tracking

locally increased flow velocity in gaps between specimen and mould

3.1.7 slowtracking

locally decreased flow velocity caused by over-compaction of the specimen along the mould edges

3.1.8 orientation angle

angle, β , between the direction of highest flow velocity, k_1 , and a reference direction, which is commonly the production direction of the material

Note 1 to entry: See [Figure 2](#).

3.2 Symbols and abbreviated terms

Symbol	Unit	Meaning
A_s	m ²	Specimen area (i.e. l_s multiplied with w_s for rectangular specimens)
$C_{1..4}$	m ²	Constants for the calculation of the principal permeabilities
CV	%	Coefficient of variation
D		Matrix containing the (x, y, z) data sets of an experiment
e		Eigenvector
f_1, f_2		Auxiliary functional terms
FS		Full scale

Symbol	Unit	Meaning
h	m	Height of the reinforcement specimen
i		Counting variable indicating the time step
J		Counting variable for experimental configurations of mould height and number of layers
k		Counting variable indicating the measurement data set
$k_{C,1}$ and $k_{C,2}$	m^2	Kozeny constants
$\bar{k}_e$	m^2	Average of experimentally measured permeability
k_e	m^2	Experimentally determined permeability
k_e^0	m^2	Experimentally determined permeability in the defined reference direction
k_e^{45}	m^2	Experimentally determined permeability orientated at an angle of 45° to the defined reference direction
k_e^{90}	m^2	Experimentally determined permeability perpendicular to the defined reference direction
k_e^{-45}	m^2	Experimentally determined permeability orientated at an angle of -45° to the defined reference direction
k_x	m^2	Permeability in flow direction
k_y	m^2	Permeability perpendicular (in-plane) to flow direction
k_1	m^2	Highest in-plane permeability
k_2	m^2	Lowest in-plane permeability
k_3	m^2	Out-of-plane permeability
$k_{1,a}$	m^2	Highest in-plane permeability, adjusted according to the actual fibre volume fraction
$k_{2,a}$	m^2	Lowest in-plane permeability, adjusted according to the actual fibre volume fraction
$\mathbf{K}$	m^2	Permeability tensor
l_s	m	Specimen length
LCM		Liquid composite moulding
m		Slope of the trend line correlating x_{mid}^2 and t
M_s	kg	Specimen mass (dry)
n		Number of measurement data sets in an experiment
n_L		Number of layers of a fibrous reinforcement in a specimen
n_T		Number of sampled data sets in a linear injection experiment
N		Number of experiments in a set
p	Pa	Array of experimental pressure values
∇p	Pa	Pressure gradient applied across the specimen, i.e. the gauge pressure applied
ΔP	Pa	Pressure drop
ΔP_{eff}	Pa	Time-averaged pressure drop
q		Coefficient in paraboloid matrix
$\mathbf{q}$		Array of coefficients from paraboloid matrix
$\hat{q}$		Coefficient in rotated matrix
Q	m^3/s	Volume flow rate
$\mathbf{Q}$		Matrix of paraboloid coefficients

Symbol	Unit	Meaning
$\mathbf{Q}_{33}$		3x3 Submatrix of paraboloid coefficients
$\hat{\mathbf{Q}}$		Matrix of rotated paraboloid coefficients
r_s	m	Specimen radius
r_1	m	Major radial extension of flow ellipse
r_2	m	Minor radial extension of flow ellipse
E_{RMSf}	m	Root mean square error of fitting the elliptic paraboloid
E_{RMSp}	Pa	Root mean square error of the pressure
s_{N-1}	m ²	Permeability standard deviation
$\mathbf{S}$		Scatter matrix
SVD		Singular value decomposition
t	s	Time
$\mathbf{t}$	s	Array of experimental timestamp values
T_{eff}	°C	Time-averaged temperature
$\mathbf{v}$	m/s	Darcy velocity vector
V		Coefficient of variation
V_f	%	Fibre volume fraction
w_s	m	Specimen width
x	m	Spatial coordinate in the reference direction of the coordinate frame of the test rig
x_{mid}	m	Shortest distance between the inlet region and the flow front position at the midpoint along the specimen width
x_{M1}	m	Shortest distance between the inlet region and the flow front position along the upper edge of the specimen in linear injection
x_{M2}	m	Shortest distance between the inlet region and the flow front position along the bottom edge of the specimen in linear injection
y	m	Spatial coordinate perpendicular (in-plane) to the reference direction of the coordinate frame of the test rig
z	s	Experimental time
α		Anisotropy ratio (k_2 / k_1)
β	degrees	Angle indicating orientation of K_1 with respect to the defined reference direction of the considered fibrous reinforcement
δ	°	Relative angle between the long cutting edge of a specimen for linear flow experiments reinforcement and the defined reference direction of the considered fibrous reinforcement
ε	m ²	Root mean square error of the flow front location x
$\varepsilon_{\text{crit}}$		Critical threshold for the race-tracking error
ε_K	m ²	Measurement error
ε_R		Race-tracking error
μ	Pa·s	Dynamic viscosity of fluid
λ		Eigenvalue
$\xi_{0...2}$		Auxiliary quantities
ρ_f	kg/m ³	Material density
ϕ	%	Porosity of reinforcement

Symbol	Unit	Meaning
w_A	kg/m ²	Areal density of a fibrous reinforcement layer (grammage)
ω	°	Smallest of the three relative angles δ selected for testing

4 Principle

A specimen of the fibrous reinforcement is compressed between two impermeable, parallel plates at a defined and uniform thickness. Then, a test fluid with known viscosity is injected at constant injection pressure through a defined inlet region, either a linear injection gate along one specimen edge or a radial injection gate in the centre of the specimen. This results in a one- or two-dimensional (i.e. linear or elliptical) flow pattern. While the reinforcement is impregnated, the flow front propagation is tracked to determine the directional flow front velocity. Data reduction schemes based on Darcy's law are applied to calculate in-plane permeability from the flow front velocity, the applied pressure gradient, the fluid viscosity, and the reinforcement porosity.

5 Design of experiments

5.1 Selection of injection method

The linear and radial test methods are equally applicable to the majority of reinforcements.

NOTE In special cases, each of the methods provides relevant specific advantages and disadvantages resulting from the different injection strategies:

- In the linear flow method, resin flows along the specimen edges. Gaps between the specimen and the mould walls can induce race-tracking, causing locally increased flow velocity compared to the bulk material. In the radial flow method, flow takes place within the specimen. However, if $k_1 \gg k_2$, the flow front in the k_1 -direction may reach the specimen edges before the minimum distance to the inlet (to obtain a stabilised flow front shape) is reached in the k_2 -direction. This would cause a calculation error as the resulting change in the pressure distribution is not considered during data processing.
- Radial injection methods allow for determination of the full in-plane permeability tensor in a single test, whereas it requires three tests in the linear injection method.
- Radial injection methods typically employ more expensive tooling than linear injection, due to the greater propensity for mould deflection owing to the larger specimen surface area.

Details on specific sources of scatter are described in detail in the publications on the results of international benchmark studies (see References [1] to [3]).

5.2 Number of repeat tests

The flow experiments defined in this document for characterization of unsaturated in-plane permeability are destructive by nature as the reinforcement specimen is irreversibly saturated with the test fluid. Therefore, repeat tests shall not be performed on a previously tested specimen. In repeat tests, new specimens with identical specifications, preferably from the same material roll/sheet, are tested at identical target conditions.

For statistical evaluation, at least five repeats shall be performed for each test condition.

NOTE Depending on the material, five repeats might still not be enough to reach a confidence interval required for certain statistical evaluations, e.g. calculation of standard deviation (see Reference [4]).

5.3 Setting the fibre volume fraction

The dependence of the in-plane permeability values on the fibre volume fraction is often of major interest. Varying the fibre volume fraction for a given reinforcement may either be done by adapting the mould cavity height, the number of layers present in the mould, or both, according to [Formula \(1\)](#):

$$V_f = \frac{n_L \cdot w_A}{\rho_f \cdot h} \quad (1)$$

All tests at a particular value of V_f shall be performed with the same number of layers, n_L . To minimize the differences in flow conditions near the mould bottom or top, and in the middle of the specimen, all tests shall be performed with the minimum values $n_{L,\min} = 4$ and $h_{\min} = 2$ mm, respectively.

The uncompressed thickness of a specimen shall be greater than the anticipated mould height for the test, to ensure tight packing of the specimen against the top mould surface.

[Formula \(1\)](#) assumes that the reinforcement consists of one type of fibre. If more than one fibre material is used, or if additional materials are present in the reinforcement, such as polymeric powder binder or stitching yarns, this shall be considered by calculating separate volume fractions for each material component, from their respective areal densities and material densities, and then adding up the component volume fractions. In this case, one should use the term “solid volume fraction” (the sum of volume fractions of all components) to point out that the solid volume consists of more than one type of reinforcing fibres or other solids.

5.4 Selecting the fluid injection pressure

The injection pressure shall not exceed 0,3 MPa.

This document does not define a minimum pressure. Yet, it is emphasized that, with decreasing injection pressure, the measurement error caused by neglecting the capillary pressure and wetting effects increases. This capillary pressure depends on the fluid/reinforcement interaction and can reach a sufficient value to have an influence on the calculated permeability. It is thus recommended to estimate the capillary pressure for the combination of test fluid and reinforcement, and to use a pressure gradient significantly higher than the estimated value (at least two times higher). A corresponding test method is, for example, described in Reference [5]. In any case, it is important to consider the wetting properties of the test fluid to evaluate the validity of the permeability value calculated. For common test fluids and fibre structures, depending on their fibre volume fraction and orientation, capillary pressures from 1 kPa to 40 kPa have been found.

NOTE The injection pressure can influence the permeability measurement. Darcy's law assumes a rigid porous media. However, reinforcements and the mould can both deform under high fluid pressure.

5.5 Temperature conditions

The test shall be performed under isothermal conditions.

5.6 Plausibility checks

After initial set-up of a new test apparatus, a basic plausibility check on the results should be performed. This can be done by performing measurements on a reference porous media such as the one described in Reference [6]. The geometrical data of this structure (including a CAD-model), as well as information on its permeability characteristics can be downloaded from: <https://standards.iso.org/iso/4410/ed-1/en>.

6 Test specimen and specimen preparation

6.1 General information

The types of reinforcement tested by the methods described in this document may be woven fabrics, non-crimp fabrics, braids, knits or non-wovens, but can also include fibre structures prepared by dry fibre placement, tailored fibre placement or similar processes. In general, this document is applicable to characterization of specimens with a quasi-homogeneous structure. [Figure 1](#) shows examples of typical reinforcements.

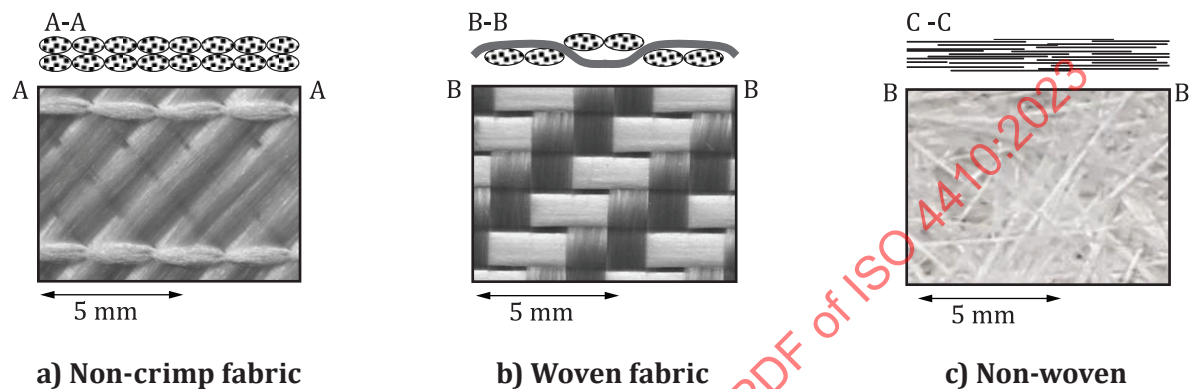


Figure 1 — Examples of reinforcement types

In the context of composite manufacturing, reinforcements are frequently made from carbon, glass or aramid fibres. Other fibre types, e.g. synthetic fibres such as polyethylene-based fibres or natural fibres such as hemp or flax, may be used. In general, this document is not restrictive in terms of the fibre material to be investigated nor its sizing, as long as there is no interaction with the fluid, such as fibre swelling due to moisture absorption or sizing dissolution.

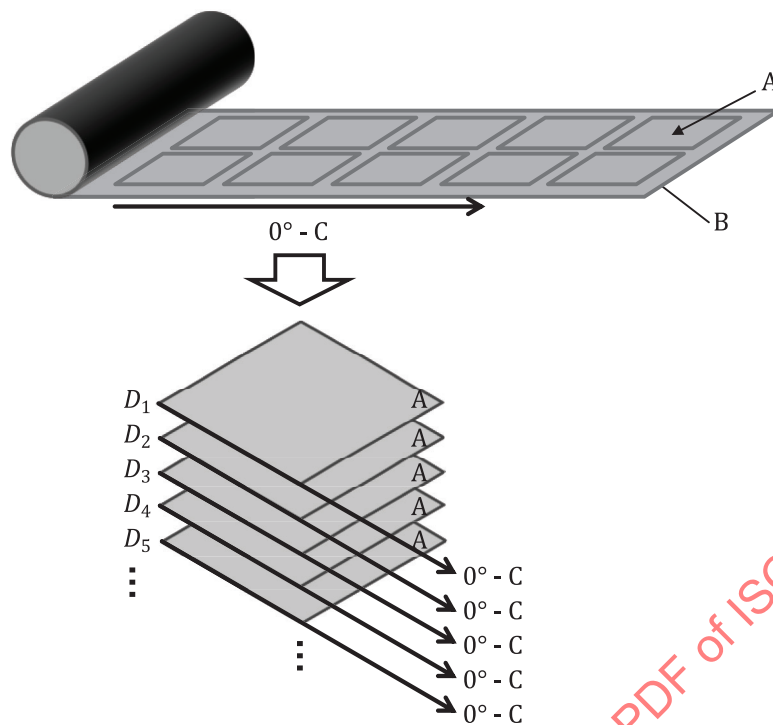
6.2 Specimen cutting

Methods, which allow high cutting accuracy to be obtained and minimize specimen deformation shall be applied. The use of computerized numerical controlled (CNC) machines is recommended. Other cutting methods can be applied if a high degree of geometrical accuracy can be obtained.

NOTE Dimensional inaccuracies and unwanted deformation induced by cutting and handling, cause errors in the calculation of the fibre volume fraction, and can contribute to unwanted race-tracking, uneven nesting and local slowtracking effects.

6.3 Specimen stacking

A reference direction and reference side shall be defined for every fibrous reinforcement to be tested. For roll materials, the production direction and top side, as illustrated in [Figure 2](#), shall be used as the reference direction and side, respectively. When intending to measure the permeability of one specific fibrous reinforcement, all layers stacked to form the specimen shall have aligned reference directions and the reference side on top (see [Figure 2](#)).

**Key**

- A top side
- B bottom side
- C production direction
- D layer

Figure 2 — Schematic illustration of production direction and top side of specimen

The reference direction and side should be marked on the specimen to ensure correct allocation of the permeability values and proper reporting.

When obtaining permeability values intended as input for numerical simulation of LCM processes, this document can generally be applied to:

- a specific multi-layer specimen comprising of one specific fibrous reinforcement, where the layers have the same or differing orientation angles or
- a specific multi-layer specimen comprising of more than one fibrous reinforcement,

as long as the validity criteria defined in [10.8.4](#) and [11.8.4](#) are fulfilled. The lay-up should then be identical to the lay-up used in the process and should be measured at the same cavity height as intended for the process. A reference direction and side of the (multi-)material should be clearly recorded. The values measured may need to be further modified when 3D flow or placement around complex curvatures (sheared permeability) is expected in numerical simulations.

NOTE Lay-ups where the layers have the same or differing orientation angles or comprise more than one fibrous reinforcement are prone to the occurrence of significant flow front distortions through the thickness, which can cause measurement error.

6.4 Specimen mass measurement

Before permeability characterization, but after cutting and stacking, the following procedure for mass (M_s) measurement shall be followed for each specimen.

- Use a scale which has an accuracy of at least $\pm 0,1$ g.

- Weigh the complete specimen directly after preparation with minimum handling in between.

Specimen handling shall be careful at any time, to minimize fraying at the edges. Fraying can lead to unwanted race-tracking effects or a reduced specimen mass and a corresponding reduction of the calculated fibre volume fraction.

7 Test fluid and fluid injection system preparation

7.1 Test fluid

The test fluid shall be a quasi-Newtonian, incompressible fluid having a viscosity between 70 mPa·s and 200 mPa·s at the test temperature (usually ambient). The temperature-dependent viscosity, $\mu(T)$, shall be tested in a relevant temperature range using a rheometer or viscometer, to be able to calculate the actual viscosity for a known test temperature. Independent of the applied test method, the accuracy concerning the fluid temperature setting and measurement shall adhere to the requirements defined in ISO 2555.

NOTE Typical fluids used for permeability characterization for fibrous reinforcements are silicone oil, rapeseed oil, motor oil, corn syrup, polyethylene glycol or fructose solutions.

7.2 Preparing the fluid and the injection system

Before adding the test fluid to the reservoir, the reservoir shall be cleaned of any residual from previously used fluid (if this was of a different kind). Information on proper cleaning agents for specific test fluids are usually available from the supplier of the test fluid.

Before starting an experiment, the pressure vessel around the fluid reservoir shall be checked for air leaks.

The complete fluid injection arrangement, including the fluid, the reservoir and the actual test apparatus, shall be placed in the room where the test is to be performed, at ambient temperature, for at least 24 h before testing.

8 Mould preparation

8.1 Specimen thickness control

The mould consists of two halves, top and bottom, arranged in a way such that the cavity is horizontally oriented, in order to avoid asymmetric gravitational forces. To ensure that the specimen thickness is uniform, the top and bottom parts of the mould shall be flat and parallel. Adjustment of the mould height shall be possible at high accuracy. Methods used for adjustment of the mould height shall not interfere with the test method. In general, all measures of the test rig shall at least correspond to tolerance class IT10 according to ISO 286-1:2010+Cor1:2013. The maximum deflection shall be <2 % of the target mould height, when the inner surfaces of the mould are pressurized to the pressures expected during testing. To obtain the required properties a metallic mould should be used. Alternatively, glass or another transparent material may be used for parts of the mould if visual flow front tracking is employed.

NOTE To adjust the mould height, often spacers, i.e. shims, are inserted between the bottom and top parts of the injection mould. Alternatively, the mould height is set using a press where the displacement is controlled through the use of linear variable differential transformers (LVDT) or laser distance sensors.

8.2 Mould height

During a permeability test, the difference between the mould height at centre and any other point in the mould shall be <2 %.

As it is generally impractical to monitor the mould height during a test, the mould height should be characterised once before the start of a test series and again at the end of a test series. A test series is a number of subsequent repeat tests (see 5.2). The mould height should be measured at five positions, as indicated in Figure 3 for specimen tested according to Method A (see Clause 10) and Figure 4 for specimen tested according to Method B (see Clause 11). For this, a specimen of the type to be tested is to be prepared, including edge sealing measures if applicable (see 10.6.1). Holes are cut in the specimen at the appropriate positions, and the specimen is placed in the mould. Small blocks of a deformable material (e.g. plasticine) are placed in the cut-out holes. The mould is closed as for permeability testing, but no test fluid is injected. The mould is re-opened, the deformable material is removed (without inducing any further deformation), and the thickness of the compressed material blocks is measured. The thickness corresponds to the (local) mould height. For the repetition of this procedure at the end of the test series, the same cut-out specimen as before can be used. To assess the cavity repeatability, it is recommended to repeat the test multiple times at each measured location.

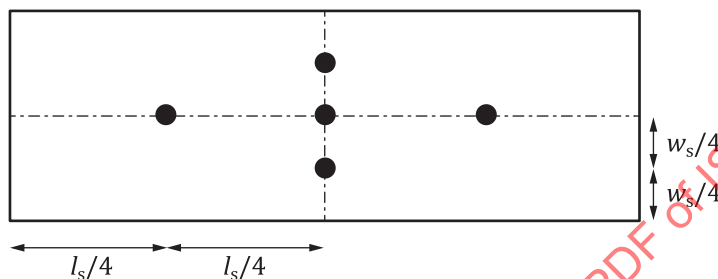


Figure 3 — Locations (five dots) for measurement of mould height for linear injection

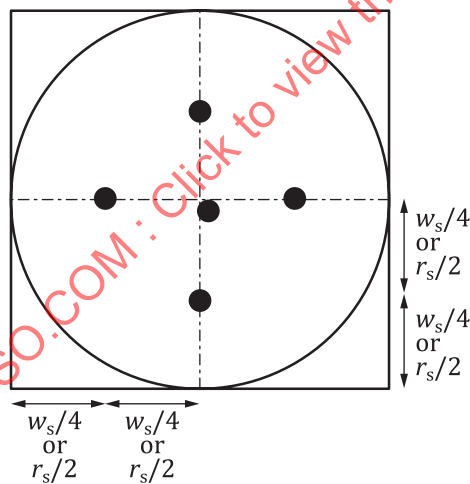


Figure 4 — Locations (five dots) for measurement of mould height for radial injection

To increase efficiency, the procedure may be performed before and after a number of test series, if these solely differ with respect to the target fibre volume fraction. In this case, the procedure should be performed with the highest intended fibre volume fraction. As the pressure on the mould surface is highest at the highest fibre volume fraction, and the risk for mould deflection is highest, it can be assumed that the requirement for the mould height (in terms of uniformity of the height) will be met for lower fibre volume fractions.

This procedure only considers errors in the mould geometry and mould deformations resulting from the mould closing load. Additional deformation induced by the injection pressure is neglected. This additional mould deformation can be evaluated by distance sensors or by numerical simulation.

8.3 Surface roughness of mould

The arithmetic mean of the absolute of the ordinate values, R_a , as defined in ISO 21920-2 shall be $\leq 0,4 \mu\text{m}$.

The surface roughness shall be measured according to ISO 21920-3 regularly to account for wear/scratching. If the roughness is found to be outside the recommended range due to wear/scratching, the tool surfaces shall be refinished.

8.4 Alignment of top and bottom part of mould

(Relative) horizontal movement of the top and bottom part of the mould during the closing process shall be prevented.

To constrain such movement, guiding pins may be used, which shall be placed outside the specimen area. This usually requires guide pin holes to be present in any spacers between top and bottom mould parts. A guiding frame, externally attached to the mould, may also be used. In any case the methods for alignment shall not interfere with the fluid flow during an injection experiment.

9 Measurement of fluid pressure, temperature and flow rate

9.1 Fluid pressure measurement

A pressure transducer shall be used for measuring fluid injection pressure. It shall be located as close as possible to the inlet region of the mould, without interfering with the fluid flow. The pressure transducer shall indicate the gauge pressure. It shall have a manufacturer's accuracy rating of 0,5 % full scale (FS) or lower with the full scale being 2 MPa or smaller.

Placing the pressure transducer as close as possible to the inlet can be done by placing it on a T-fixture, where it is located opposite to the inlet.

A second pressure sensor located near the outlet region can be used to ensure that the vent remains clear of any obstruction.

9.2 Fluid temperature measurement

A temperature sensor shall be placed either in the mould or feed line, as close as possible to the inlet. A temperature measurement of the fluid is required for accurate calculation of the fluid viscosity.

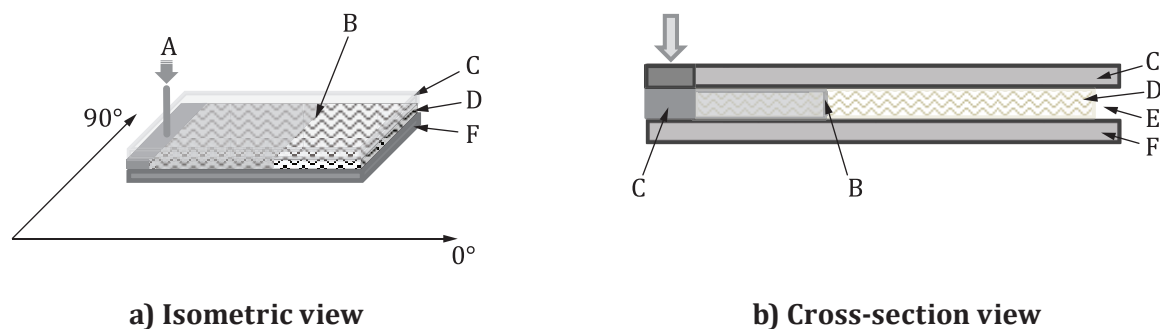
9.3 Fluid flow rate measurement

Flow rate measurement may be used to supplement the flow front location measurements. For this, a flow rate sensor can be placed anywhere between the pressure vessel and the injection mould, but before the pressure sensor for inlet pressure measurement. It shall then provide an accuracy of $\pm 1 \%$ in the range of interest. Alternatively, scales can be used to determine the flow rate from mass changes of the fluid reservoir. The accuracy of the scales shall then be at least $\pm 0,1 \text{ g}$.

10 Method A: Linear flow experiments

10.1 Apparatus design

Unsaturated linear injection entails the fluid impregnation of a rectangular reinforcement specimen through a linear injection gate, ideally resulting in one-dimensional flow front propagation, see [Figure 5](#).



Key

A	fluid inlet	D	specimen
B	flow front (tracked)	E	vent region
C	top plate	F	bottom plate

Figure 5 — Schematic illustration of the unsaturated linear injection approach

For the unsaturated linear injection method, the apparatus shall allow the following.

- A specimen made of reinforcement layers is compressed between two rigid mould surfaces at uniform gap height.
- A test fluid is injected into a rectangular distribution chamber, located upstream of the specimen, at constant injection pressure.
- An unsaturated measurement principle is applied, i.e. the flow front position is measured at various time intervals.
- A vent is placed at the end opposite to the injection inlet to allow displaced air and test fluid to escape from the mould.
- No vacuum is applied at the vent before or during the injection.

10.2 Specimen planar dimensions

The range for specimen length, l_s , shall be 300 mm to 600 mm, while the specimen width, w_s , should be 150 mm. Other specimen widths may be accommodated, but will have a significant but undetermined effect on the validity criteria described in [10.8.4](#). In any case, w_s should be in the range of 100 mm to 200 mm.

The specimen size shall be wide enough to mitigate any edge flow effects, and long enough for a straight flow front to develop. On the other hand, very wide specimens have a greater risk of mould deflection, and very long specimens can cause flow velocities slow enough for capillary forces to significantly affect the measurement.

10.3 Injection gate geometry

The injection gate shall be located at one short edge of the rectangular specimen, so that the injected fluid fills the entire mould cross-section before entering the specimen (see [Figure 5](#)). The injection gate is effectively an empty channel, which should have a width of at least 10 mm. The hole for connection of the feed line shall be smaller than the injection channel width.

10.4 Vent geometry

A vent shall be placed at a short edge of the rectangular specimen, opposite the injection gate. The vent is an empty gap, between the end of the specimen and the end of the mould cavity, containing an opening connecting the inside of the mould to ambient pressure.

10.5 Fluid injection system

[Figure 6](#) shows a schematic illustration of the fluid injection system. The fluid reservoir is located within a pressure vessel, which shall be able to set a target pressure with an accuracy of $\pm 2\%$. Tubes leading from the fluid reservoir to the inlet point (feed line) shall be as short as possible to minimize pressure losses. A maximum length of 2 m shall not be exceeded. The inner tube diameter shall be between 10 mm and 15 mm. Setting the pressure should be done via an electric proportional valve.

NOTE Smaller tube diameters than the defined values can increase pressure losses.

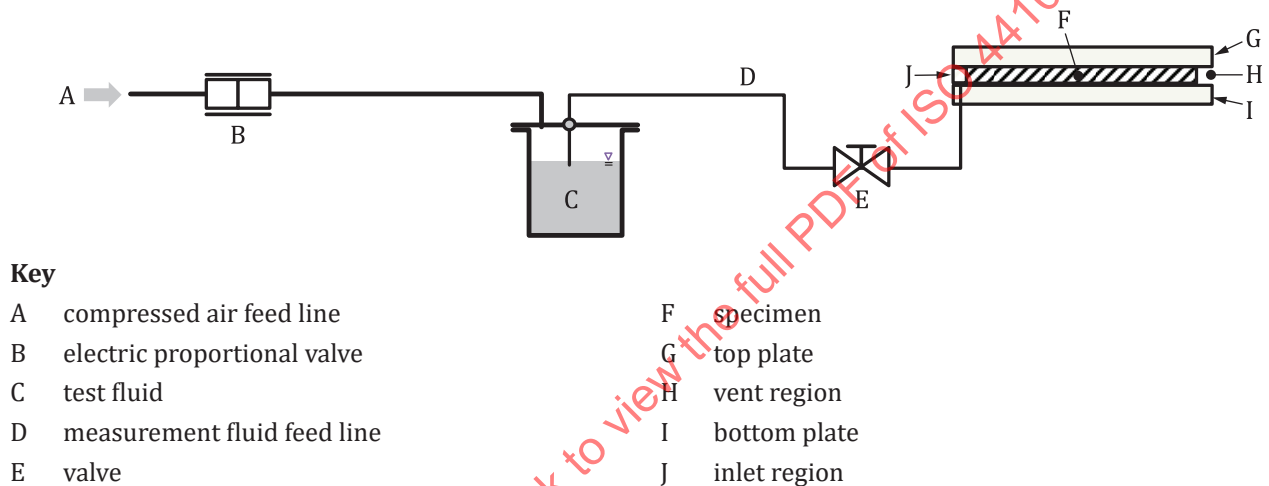


Figure 6 — Schematic illustration of the linear method fluid injection system

10.6 Test preparation

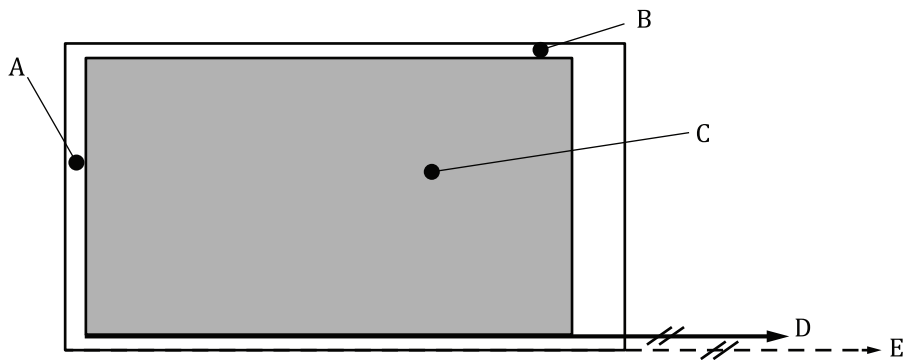
10.6.1 Edge sealing

To prevent race-tracking in linear injection experiments, gaps between the mould and the specimen shall be sealed along the entire specimen length. The width of the applied sealant shall be constant and considered during calculation of the effective specimen width.

Sealing can be done, for example, using silicone gaskets or paste, or injection of gelatine at the specimen edges.

10.6.2 Placing the specimen in the mould

When placing the specimen in the mould, the long cutting edge of the specimen shall be accurately aligned with the reference axis of the mould (see [Figure 7](#)). The defined reference side of the specimen shall face upwards.



Key

- | | | | |
|---|----------------------------------|---|-----------------------------------|
| A | inlet region | D | long cutting edge of the specimen |
| B | mould | E | reference direction of the mould |
| C | specimen (reference side on top) | | |

Figure 7 — Alignment of specimen orientation with reference axis of the mould

Tests at three different test directions relative to the reference direction shall be performed, differing by 45°.

For correct data analysis and reporting, the relative angle, δ , between the long cutting edge of the material, which is aligned with the reference direction of the mould and the defined reference direction of the material shall be known at any time.

NOTE Two of the three measurement directions are typically chosen to be close to the symmetry directions of the fabric (for example, warp and weft in woven fabrics, production and cross direction in braids, course and wale in knits). The third reference direction is then the bisecting angle between the other two directions.

10.7 Sensor equipment/Data acquisition

10.7.1 Fluid flow front measurement

Flow front monitoring shall be performed along the principal flow direction, at various values of t , the time from when the fluid first touches the specimen. At n_T intervals in time t , the flow front shall be captured. For the i th measurement at time t_i , the location of the flow front shall be measured at three locations, $(x_{mid}, x_{M1}, x_{M2})_i$, representing the midpoint of the flow front and points at each edge of the specimen (see [Figure 8](#)).

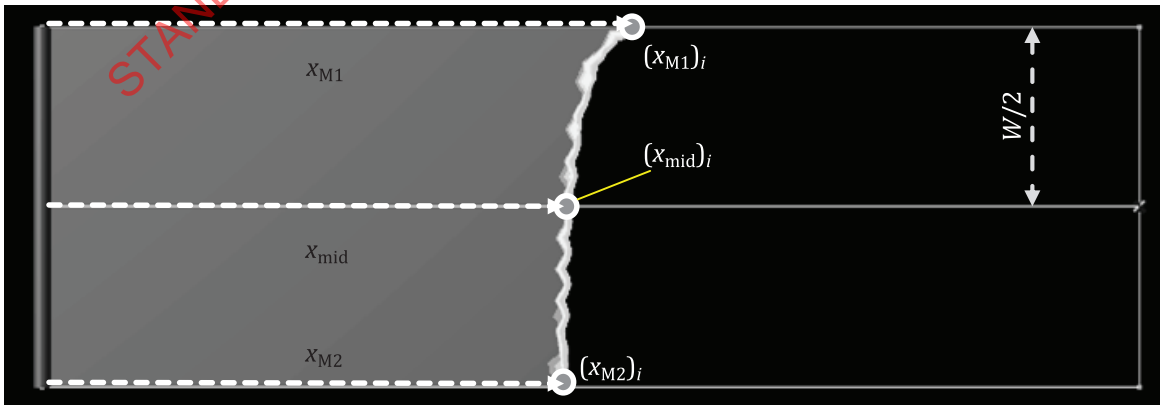


Figure 8 — Example flow front location measurement

To avoid errors and inaccuracies resulting from flow starting effects, no flow front data captured in a distance less than 20 mm from the inlet region shall be used.

When applying visual observation, each photograph should go along with some reference length scale so as to determine the flow front position through post-experiment image analysis. The camera should be positioned to point as perpendicular to the in-plane reinforcement surface as possible, to minimize measurement error from perspective distortion. The reference scale should be in the same plane as the sample. In place of visual observation, other sensors may be used to determine each value of $(x_{\text{mid}}, x_{\text{M1}}, x_{\text{M2}})_i$. The sensors should then be placed along the middle line and along each specimen edge in order to record the necessary data. The distance between the sensors along the flow direction should be as short as possible to improve measurement resolution.

10.7.2 Sampling of measurement data

The number n_T of measurements of the flow front location shall be as high as reasonably possible in order to ensure representative sampling of the flow progress; the minimum shall be $n_T = 10$. Fluid temperature and pressure at the inlet should be correlated with exactly the times when flow front measurements take place, but shall at least be done at an equal acquisition rate, i.e. at least 10 measurements over the experiment's duration.

10.8 Data processing

10.8.1 Data segmentation

For the data processing procedure to apply, constant fluid injection pressure is assumed. However, typical characteristics of fluid injection pressure readings show a distinct pressure build-up in the starting stage of the experiment as schematically shown in [Figure 9](#). Here, the axis show p and t , pressure and time, Δp_{eff} is the time-averaged pressure drop, t_{sep} is the time of separation and t_{total} is the total experiment time.

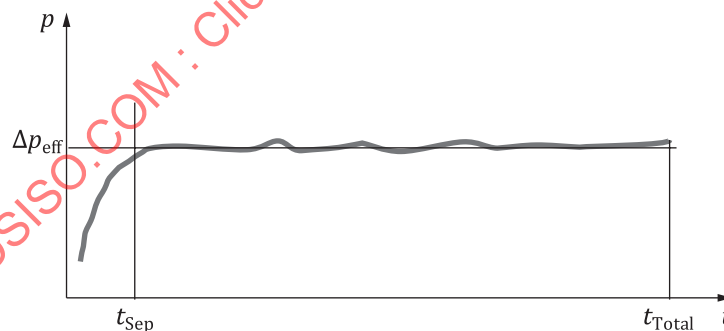


Figure 9 — Typical characteristics of fluid injection pressure

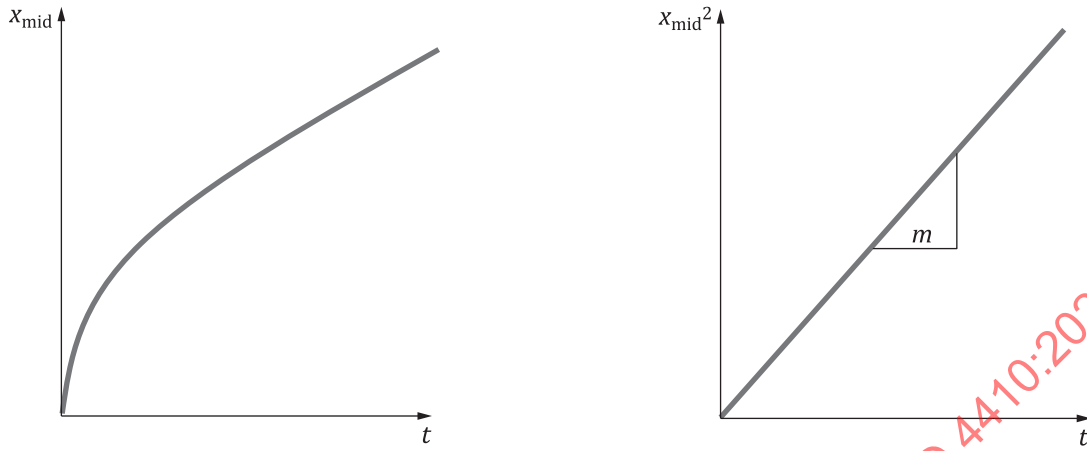
The data from this starting stage shall be eliminated prior to the subsequent processing steps. For this purpose, $t_{\text{sep}} = s t_{\text{total}}$ shall be chosen with: $0 < s < 0,1$. Data segmentation shall be applied to all relevant measurement data, in particular fluid injection pressure, fluid temperature and flow front location.

In addition, invalid data at the end of the experiment, e.g. acquired after closing the feeding line, shall be eliminated prior to subsequent processing steps.

10.8.2 Data evaluation procedure

Determination of the permeability is based on a linear interpolation of the squared flow front position along the middle of the specimen, x_{mid}^2 . A plot of $x_{\text{mid},i}$ versus t_i should look similar to the one in

[Figure 10](#) a). The flow front position x_{mid} shall then be squared and plotted versus t . According to Darcy's law, this should result in a straight line through the origin, as depicted in [Figure 10](#) b).



a) Typical flow front position versus time

b) Squared flow front position versus time

Figure 10 — Schematic graph of flow front position change over time under constant pressure conditions

A linear trend line shall then be obtained from this data. The slope of this trend line, m , is then determined for the calculation of permeability. For a constant pressure injection, the permeability of the specimen shall be evaluated based on Darcy's law, as shown in [Formula \(2\)](#):

$$k_e = \frac{x_{\text{mid},i}^2}{2\Delta P_{\text{eff}} t_i} \phi \mu(T_{\text{eff}}) \quad (2)$$

where ϕ is the porosity, $\phi = 1 - V_f$.

The viscosity $\mu(T_{\text{eff}})$ is a function of the time-averaged temperature (T_{eff}). This and the time-averaged pressure drop (ΔP_{eff}) are calculated from the measurements of the temperature T and applied pressure drop ΔP (the gauge pressure applied on the inlet), respectively, for each of the n_T measurements of the flow front position, according to [Formulae \(3\)](#) and [\(4\)](#):

$$T_{\text{eff}} = \sum_{i=1}^{n_T-1} \frac{T_i (t_{i+1} - t_i)}{t_{n_T} - t_1} \quad (3)$$

and

$$\Delta P_{\text{eff}} = \sum_{i=1}^{n_T-1} \frac{\Delta P_i (t_{i+1} - t_i)}{t_{n_T} - t_1} \quad (4)$$

Using [Formulae \(3\)](#) and [\(4\)](#) and the slope m of the graph shown in [Figure 10](#) b), the experimental permeability value shall be obtained using [Formula \(5\)](#):

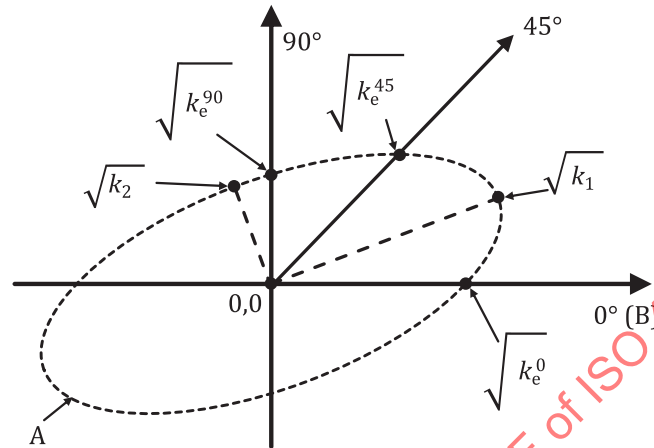
$$k_e = \frac{m}{2\Delta P_{\text{eff}}} \phi \mu(T_{\text{eff}}) \quad (5)$$

The error of the measurement ε_K [mean square root error of the regression $\times \sim$ square root (t)] using this analysis technique shall be estimated according to [Formula \(6\)](#):

$$\varepsilon_K = \frac{1}{n} \sum_{i=1}^n (x_{\text{mid},i} - \sqrt{m t_i})^2 \quad (6)$$

10.8.3 Calculating the permeability tensor

The square root of the effective in-plane permeability along a specific direction, k_e , follows an ellipse as displayed in [Figure 11](#), where the semi-major and semi-minor axes represent the square roots of the principal in-plane permeability values, k_1 and k_2 . The in-plane permeability tensor shall be estimated by measuring the effective permeability of the fibrous reinforcement, k_e , in three different directions.



Key

- A in-plane permeability ellipse
- B reference direction of fibrous reinforcement

Figure 11 — Elliptic pattern of the in-plane permeability tensor showing the effective permeabilities

As mentioned in [10.6.2](#), three sets of N experiments shall be carried out to evaluate the permeability tensor of a preform, where N is at least five (see [5.2](#)). The five specimens for the first, second, and third set shall be oriented at $0^\circ + \omega$, $90^\circ + \omega$ and $45^\circ + \omega$ with respect to the reinforcement reference direction. Commonly $\omega = 0$, resulting in what is depicted in [Figure 11](#). From the effective permeabilities (k_e) measured in each direction, the principal permeabilities are computed by [Formulae \(7\)](#) to [\(13\)](#). The average k_e over the N experiments for each orientation is used in [Formulae \(7\)](#) and [\(8\)](#):

$$k_1 = k_e^0 \frac{C_1 - C_2}{C_1 - \frac{C_2}{\cos(2C_3)}} \quad (7)$$

$$k_2 = k_e^{90} \frac{C_1 + C_2}{C_1 + \frac{C_2}{\cos(2C_3)}} \quad (8)$$

Here C_1 , C_2 , and C_3 are determined using [Formulae \(9\)](#), [\(10\)](#) and [\(11\)](#), respectively:

$$C_1 = \frac{k_e^0 + k_e^{90}}{2} \quad (9)$$

$$C_2 = \frac{k_e^0 - k_e^{90}}{2} \text{ and} \quad (10)$$

$$C_3 = \frac{1}{2} \tan^{-1} \left(\frac{C_1}{C_2} - \frac{C_1^2 - C_2^2}{k_e^{45} \cdot C_2} \right) \quad (11)$$

The orientation angle β between k_1 and the reinforcement reference direction shall be determined using [Formula \(12\)](#):

$$\beta = \frac{1}{2} \tan^{-1} \left(\frac{2C_4}{\left(1/k_e^0\right) - \left(1/k_e^{90}\right)} \right) \quad (12)$$

where C_4 is given by [Formula \(13\)](#):

$$C_4 = \frac{1}{k_e^{45}} - \frac{1}{2k_e^0} - \frac{1}{2k_e^{90}} \quad (13)$$

10.8.4 Validity checks

Tests shall be excluded from the data post processing if any one of the following criteria is not fulfilled:

— Test conditions:

- the temperature of the mould, fabrics and fluid differ by no more than $\pm 0,5$ °C from T_{eff} [defined in [Formula \(3\)](#)];
- the coefficient of variation ε_p of the fluid pressure as specified in [Formula \(14\)](#), shall be smaller than 2 %:

$$\varepsilon_p = \frac{\sigma_p}{\Delta P_{\text{eff}}} \quad (14)$$

with σ_p defined according to [Formula \(15\)](#):

$$\sigma_p = \sqrt{\frac{n_T}{n_T - 1} \sum_{i=1}^{n_T-1} \left(\frac{(\Delta P_i - \Delta P_{\text{eff}}) (t_{i+1} - t_i)}{t_n - t_1} \right)^2} \quad (15)$$

- When the specimen edge is not properly sealed against the mould walls, a preferential flow path may occur along that edge which is known as race-tracking. This phenomenon usually causes an over-estimation of the measured permeability value. The opposite case is a less common phenomenon known as “slowtracking” which is caused by over-compaction of the reinforcement along the edges. In either case, and whether the edge-effects occur along one edge or both edges, a measure of the edge-effect error shall be determined by calculating the measure of race-tracking error as defined in [Formula \(16\)](#):

$$\varepsilon_{R,i} = \frac{x_{M1,i} + x_{M2,i} - 2x_{\text{mid},i}}{2w_s} \quad (16)$$

The error $\varepsilon_{R,i}$ shall be evaluated for each time measurement $(x_{\text{mid}}, x_{M1}, x_{M2})_i$. For any i th measurement at time t_i , $\varepsilon_{R,i}$ shall be compared to a critical threshold $\varepsilon_{\text{crit}}$, which is calculated as a function of the ratio of the permeability k_x in the flow direction (parallel to long cutting edge of specimen) and the permeability k_y perpendicular to the flow direction and the specimen length (l_s) according to [Formula \(17\)](#):

$$\varepsilon_{\text{crit}} = 0,06 \cdot \ln \left(\frac{k_x}{k_y} \right) - (0,12 m^{-1}) l_s + 0,115 \quad (17)$$

Determining $\frac{k_x}{k_y}$ requires both k_e^0 and k_e^{90} tests to have already been performed. When testing k_e^0 , k_x is equivalent to k_e^0 and k_y is equivalent to k_e^{90} , and vice-versa. For k_e^{45} experiments, k_y (in the -45° direction) shall be determined from a geometric transformation, once all three experiments (k_e^0 , k_e^{90} , and k_e^{45}) have been performed, and k_1 and k_2 have been calculated (see 10.8.2), using Formula (18):

$$k_y = k_e^{-45} = \frac{k_1 k_2}{k_2 \cos^2(\beta + 45^\circ) + k_1 \sin^2(\beta + 45^\circ)} \quad (18)$$

Formula (17) represents a 5 % over-estimation of the true permeability, for most flow scenarios with $w_s = 150$ mm. For any data point when $\varepsilon_{R,i}$ exceeds ε_{crit} , that measurement is significantly affected by race-tracking, and all data of $(x_{mid}, x_{M1}, x_{M2})_i$ for that value of i and all subsequent measurements shall be excluded from the results. This allows validation (usage) of any measurements made before the onset of significant race-tracking. For some cases where the overall measurement error is high, and 5 % is not as significant of an error contribution, then data with $\varepsilon_{R,i} > \varepsilon_{crit}$ may be included in the reported data as long as the operator notes the values for $\varepsilon_{R,i}$.

For a specimen width w_s other than 150 mm, an estimation of $\varepsilon_{crit}(w_s)$ shall be made for anisotropy ratios close to 1 ($k_e^0 \approx k_e^{90}$) by adjusting the ε_{crit} as determined in Formula (17) in the way described by Formula (19):

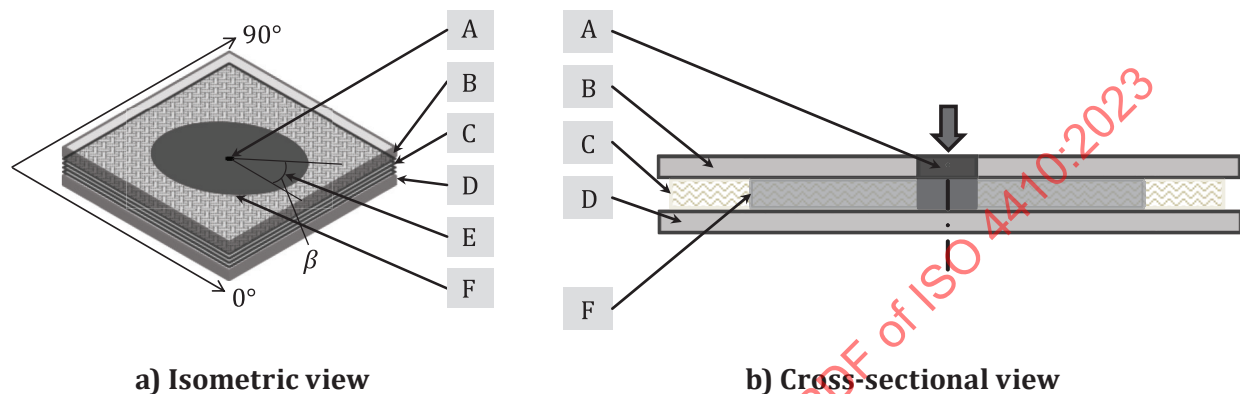
$$\varepsilon_{crit}(w_s) = \left[0,4 \left(\frac{w_s}{150} \right) + 0,61 \right] \cdot \varepsilon_{crit} \quad (19)$$

When testing a bias flow specimen (k_e^{45}) if the reinforcement has a low anisotropy ratio ($k_e^0 \gg k_e^{90}$), a measurement error will occur due to a time-dependent change in the shape of the flow front. A symptom of this case is a diagonal flow front, i.e. where the flow front may be straight but not perpendicular to the flow direction. In this case, this acceptance criterion may result in a failed test despite no race-tracking. Thus, if the anisotropy ratio is low and the orientation β is unknown, the radial test method is recommended over this linear method.

11 Method B: Radial flow experiments

11.1 Apparatus design

Radial injection entails the fluid impregnation of a reinforcement specimen through a central injection gate, ideally resulting in two-dimensional flow with an elliptical flow front, see [Figure 12](#).



Key

A	central injection hole	D	bottom plate
B	top plate	E	orientation angle β
C	specimen	F	flow front (tracked)

Figure 12 — Schematic illustration of the radial injection approach

For the radial injection method, the apparatus shall allow the following.

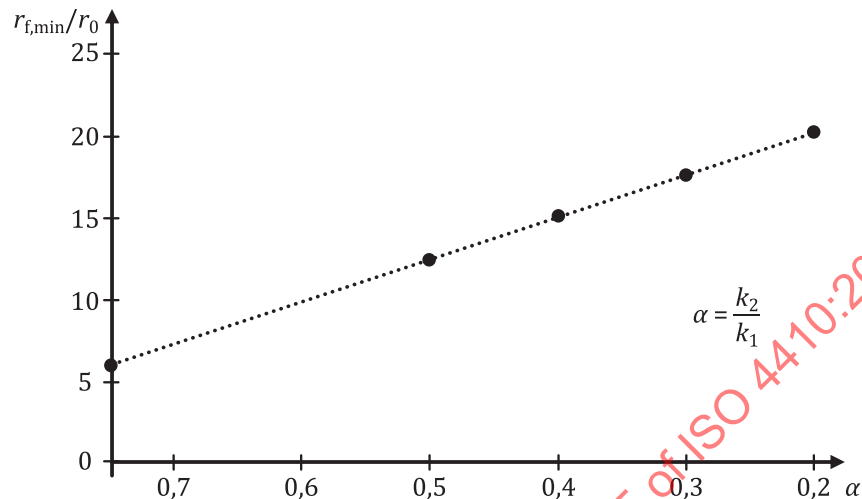
- A specimen made of reinforcement layers is compressed between two rigid mould surfaces at uniform gap height.
- A test fluid is injected through a central circular hole at a given injection pressure.
- An unsaturated measurement principle is applied, i.e. the flow front position is measured at various time intervals.
- A vent is placed along the outer edge of the mould to allow displaced air and fluid to escape from the mould.
- No vacuum is applied before or during the injection.

11.2 Specimen planar dimensions

The specimen size shall be large enough for a constant aspect ratio of the elliptical flow front to develop. For square specimens, the edge length shall be at least 30 times the radius of the injection gate. This will allow anisotropic permeabilities with anisotropy ratios, α , between 1,0 and 0,4 to be determined. If α is smaller, larger dimensions are required. [Figure 13](#) shows the minimum flow radius, $r_{f, \min}$, required for flow front development. As the specimen shall accommodate for twice the length of the radius, for any anisotropy ratio below 0,4, the ratio of specimen edge length to injection gate radius, r_0 , shall be at least twice the corresponding ratio seen in the ordinate of [Figure 13](#). For example, an anisotropy ratio of 0,2 would require a 20 multiplier for the flow radius, and thus a ratio of 40 between

the minimum specimen edge length and injection gate radius. Specimen dimensions may be larger, as long as requirements on mould deflection can be met.

NOTE Very wide specimens have a greater risk of mould deflection and can cause a flow velocity slow enough for capillary forces to significantly affect measurement.



NOTE Adapted from Reference [7].

Figure 13 — Minimum flow front “radius”, $r_{f,min}$, along the major principal flow direction, i.e. major ellipse axis k_1 , for convergence of flow front shape as a function of the anisotropy ratio (for $r_0 = 8$ mm)

11.3 Injection gate geometry

For practical reasons, the injection gate should be positioned in the centre of the mould. The injection gate shall be circular and the diameter should be 10 mm. Other diameters of the injection gate may be used, as long as the specimen size follows the guidelines in 11.2, and the circular hole in the specimen remains as large, or larger than the gate.

When tracking the flow front by optical means, occlusion of the advancing flow front should be avoided, e.g. by arranging the camera system on the opposite side of the mould to the injection gate and the feeding line. For easier operation, the injection gate should be in whichever part of the mould remains stationary when loading a specimen, and opposite the transparent tool side.

11.4 Vent geometry

The entire circumference of the specimen shall be vented, i.e. connect the inside of the mould to ambient pressure.

For practical reasons, a circular channel may be machined in the bottom part of the mould, surrounding the specimen, to drain the test fluid. Dimensions for such a flow channel should be 10 mm in width and 10 mm in depth. Fluid is drained from the channel through holes in the bottom of the mould.

11.5 Fluid injection system

Figure 14 shows a schematic illustration of the fluid injection system. The fluid reservoir is located within a pressure vessel, which shall be able to set a target pressure with an accuracy of ± 2 %. Tubes leading from the fluid reservoir to the inlet point (feed line) shall be as short as possible to minimize pressure losses. A maximum length of 2 m shall not be exceeded. The inner tube diameter shall be between 10 mm and 15 mm. Setting the pressure should be done via an electric proportional valve.

NOTE Tubes with a diameter smaller than the defined values can lead to excessively high pressure losses.

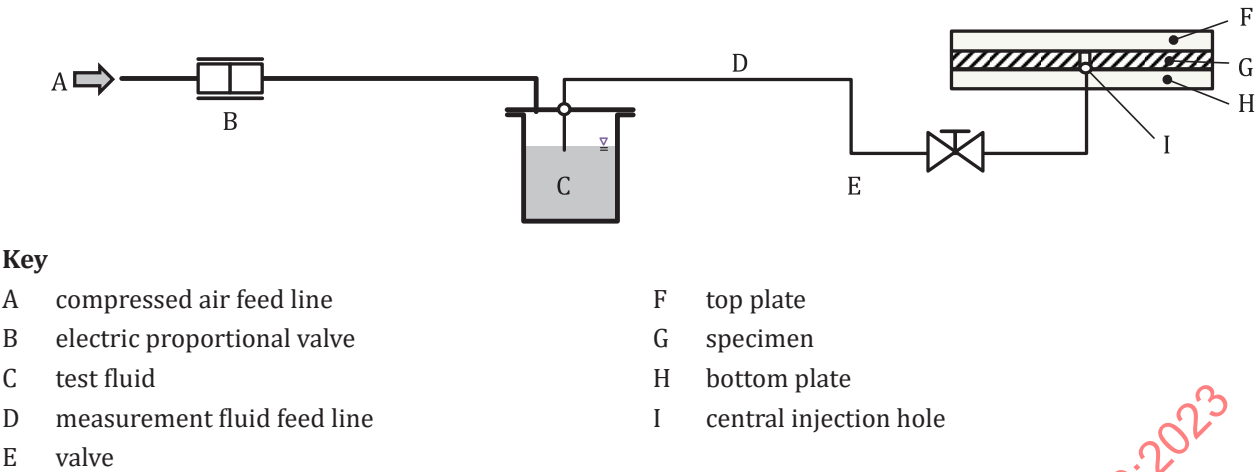


Figure 14 — Schematic illustration of the radial method fluid injection system

11.6 Test preparation

11.6.1 Inserting the inlet hole in the specimen

There shall be a circular hole in the specimen of the same diameter as (or slightly larger than) the hole in the mould where the feed line is connected (see 11.3). The hole shall go through the complete specimen from top to bottom. For textiles, the hole should be punched using a round hole punch. If the hole is integrated into the individual layers before stacking, offset of the hole position shall be prevented by all means.

NOTE The hole geometry is relevant for the data processing. The geometrical accuracy of the inlet hole is therefore crucial for the measurement accuracy. Cutting the hole instead of punching it can result in yarns being pushed aside and moving back afterwards.

11.6.2 Placing the specimen in the mould

When placing the specimen in the mould, the cutting edge of the specimen shall be accurately aligned with the reference axis of the mould (see Figure 15). The defined reference side of the specimen shall face upwards. The injection holes in the mould and the specimen shall be concentric.

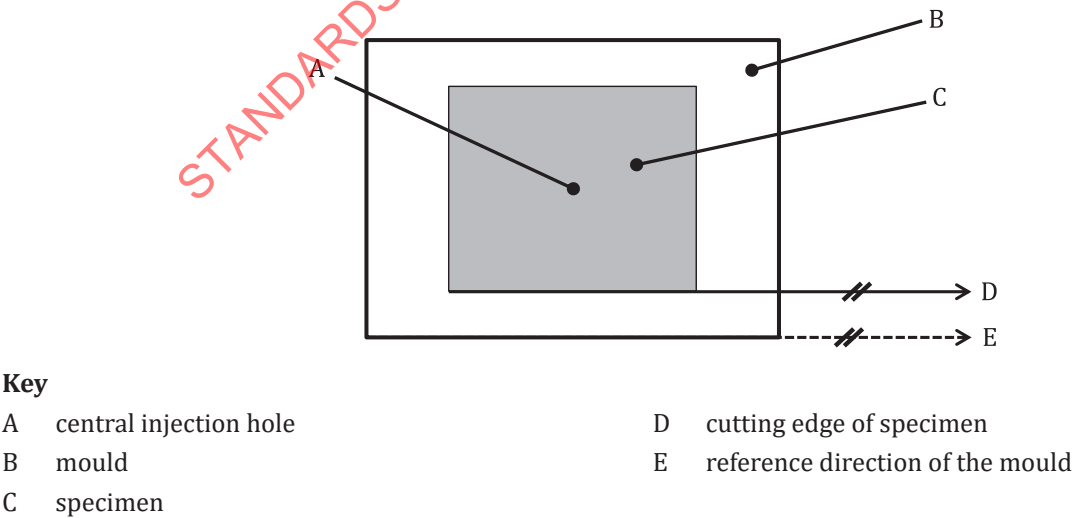


Figure 15 — Alignment of specimen orientation with reference axis of the mould

For correct data analysis and reporting, especially of the orientation angle β of the principal flow direction, the relative angle between the reference direction of the mould and the defined reference direction of the material (see [Figure 2](#)) should be known at any time.

11.7 Sensor equipment/Data acquisition

11.7.1 Fluid flow front monitoring

The flow front position shall be measured either by optical photography, capacitive line sensors or point sensors. Flow front measurement shall be made either quasi continuously, or for at least 9 spatial instances. If using point sensors, these shall either be placed along lines in at least 3 directions originating from the central inlet or shall be well-distributed across the mould.

If only the minimum of three directions is monitored, these directions should be 0° , 90° and 225° relative to the reference direction of the specimen.

When applying visual observation, the camera should be positioned to point as perpendicular to the in-plane reinforcement surface as possible, to minimize measurement error from oblique angles. The lens distortion can be detected and quantified by placing graph paper on the transparent surface.

11.7.2 Sampling of measurement data

Flow front measurement shall be made either quasi continuously, or for at least 9 spatial instances. Fluid temperature and pressure (inlet) shall be captured at exactly the times when flow front measurement takes place.

11.8 Data processing

11.8.1 Data evaluation range

A minimum distance needs to be covered by the propagating flow front before data can be acquired. The minimum distance in terms of the injection gate radius is indicated in [Figure 13](#) (see [11.2](#)).

11.8.2 Data segmentation

For the data processing procedure to apply, constant fluid injection pressure is assumed. However, typical characteristics of fluid injection pressure readings show a distinct pressure build-up in the starting stage of the experiment as schematically shown in [Figure 16](#). Here, the axes show p and t , pressure and time, where Δp_{eff} is the time-averaged pressure drop, t_{sep} is the time of separation and t_{total} is the total experiment time.

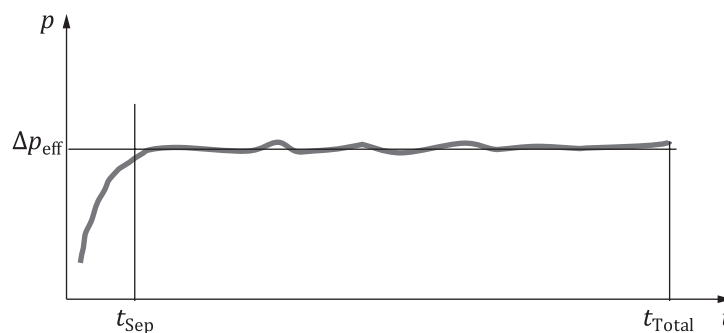


Figure 16 — Typical characteristics of fluid injection pressure

The data from this starting stage shall be eliminated prior to the subsequent processing steps. For this purpose, $t_{\text{sep}} = s t_{\text{total}}$ shall be chosen with: $0 < s < 0,1$. Data segmentation shall be applied to all

relevant measurement data, in particular fluid injection pressure, fluid temperature and flow front location.

In addition, invalid data at the end of the experiment, e.g. acquired after closing the feeding line, shall be eliminated prior to subsequent processing steps.

11.8.3 Data processing algorithm

11.8.3.1 General

In the following subclauses, a general methodology for evaluating the data acquired during the radial flow experiment is provided and shall be applied. In particular, it considers the different type and nature of the flow front measurement method (see [Figure 17](#)):

- a) quasi-continuous flow front data from areal sensors, such as the sequential images of a camera system evaluated by digital image processing algorithms;
- b) sensor saturation data as e.g. from linear capacitive sensors; or
- c) flow arrival time data as derived e.g. from pressure or electric point sensors.

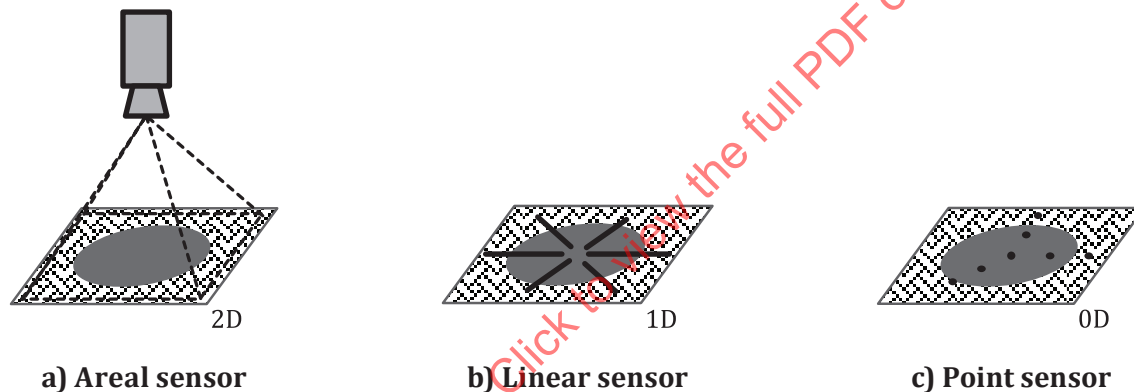


Figure 17 — Sensor types used for flow front tracking in radial flow experiments

11.8.3.2 Collecting flow front data over experimental time

The data describing the temporal advancement of the fluid flow front shall be collected in a combined time-space-coordinate system (see [Figure 18](#)). Therein, the x - and y -direction represent spatial coordinates, which reflect the coordinate frame of the test rig, whereas the z -direction reflects the experiment time.

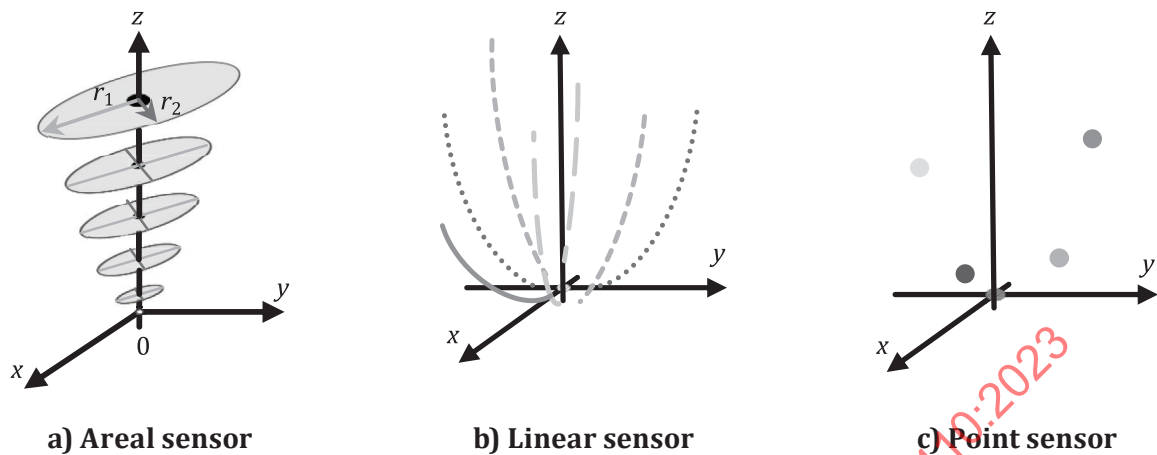


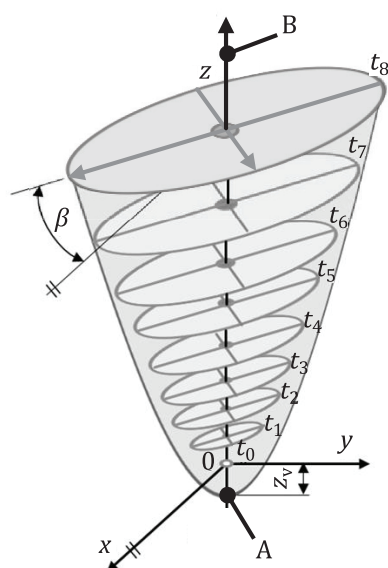
Figure 18 — Collecting the data describing the temporal advancement of the fluid flow front in a three-dimensional coordinate frame

NOTE Although the representation of the data in this combined time-space-coordinate system is general, i.e. independent of the data source, the actual error metric to be minimized in the subsequent model approximation routine varies according to the source and the statistical nature of the data:

- a) flow front data derived from an areal sensor shows uncertainty along the x - and y -coordinates, but negligible uncertainty in the corresponding time data;
- b) for linear capacitive sensors, the uncertainty is associated with the saturation length, which can be seen as the radial distance in a polar coordinate frame, while the associated polar angle as well as the time data show negligibly small uncertainty;
- c) the data derived from point sensors exhibits statistical uncertainty in the flow arrival time information only while the corresponding spatial data, i.e. the physical location of the point sensors, is deterministic.

11.8.3.3 Geometric model approximation

The geometric model of an elliptic paraboloid (see [Figure 19](#)) shall be approximated to the complete fraction of the collected data describing the temporal advancement of the fluid flow front, that is within the permissible data evaluation range (see [11.8.1](#)).



Key

A paraboloid vertex

B paraboloid axis

NOTE Adapted from Reference [7].

Figure 19 — Approximation of an elliptic paraboloid model to the data describing the temporal advancement of the fluid flow front

NOTE The fitted elliptic paraboloid shows the following properties (see Reference [7]):

- the primary axis of the paraboloid is aligned with the z -axis;
- the vertex is located on the z -axis at a particular distance from the origin; and
- the major axis of the elliptic cross-section of the paraboloid is oriented at an angle β with respect to the $x-z$ -plane.