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Fluid mechanical evaluation of in-line filter for fluid-handling systems by means of computational fluid dynamics (CFD)

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Abstract: Administering fluids and drugs intravenously is crucial in caring for vulnerable patient cohorts such as critically ill patients as well as neonatal and paediatrics patient populations. Studies have revealed severe contamination of infusion solution that could be avoided by utilizing in-line filters. The filtration performance consequently depends on the geometry of the filter housing. The purpose of our numerical study was to analyse the flow situation in filter housings depending on the geometry (diameter of the filter housing and distance between entrance and membrane). We compared the flow of two circular filter system with different housing width (D = 25 mm; L = 1.5 mm/3.0 mm) by means of computational fluid dynamics (CFD). The filter membrane was modelled by a porous jump condition. Both filter systems showed a highly reduced inflow on the membrane compared to the velocity in the Luer Lock ports. The wide filter housing facilitates a more homogenous inflow on the membrane (>92% of the membrane area is applied within a range of 5% of the mean velocity) compared to the narrow filter housing. Despite that difference both filter housings induced a well distributed flow through the filter membrane. However, for large filter systems (>50 mm diameter) the design of the filter housing could play a crucial role in optimising filter performance and therefore CFD should be considered.

Keywords: In-line filter, CFD, porous jump, homogenous flow, filter membrane

1 Introduction

Administering fluids and drugs intravenously is crucial in caring for vulnerable patient cohort such as critically ill patients as well as neonatal and paediatrics patient populations [1,2,3]. Studies have revealed contamination with glass particles from opening glass ampoules, rubber stopper particles, and conglomerates of parenteral nutrition components [4]. Several studies have shown that the particle load of a patient can be up to several 100,000 particles per day, depending on the complexity of the infusion therapy and the infusion system [3]. The potential contamination of infusion solutions by particles is often overlooked [5], although filters can potentially retain glass, rubber and plastic particles as well as particles from drug incompatibilities, air, microorganisms (bacterial size 1-3 µm), and smaller endotoxins [6].

Clinical studies have demonstrated the safety and efficacy of in-line filtration in preventing complications in patients in the intensive care unit (ICU) [1,2,3].

Filtration systems for infusion therapy come in a huge variety in housing and membrane geometries. The medium to be filtered is distributed depending on the flow situation upstream and downstream of the membrane and therefore on the geometry of the filter housing. The filtration performance consequently depends on the geometry of the filter housing.

Nevertheless, to the best of the authors' knowledge, no fluid mechanical analyses of the internal flow of medical in-line filters can be found in the literature. Within this study we concentrated on cylindrical designs rather than flat filters. Often, cylindrical filters are designed with a centric inflow and outflow.

The purpose of our numerical study was to analyse the flow situation in filter housings depending on the geometry, particularly the diameter of the filter housing and the distance between entrance and membrane.

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2 Materials and Methods

2.1 Filter geometries

Geometrically, the numerical model consists of an inlet and outlet tube, a cylindrical filter housing and an infinite thin filter membrane, see Figure 1. The inner diameter of the filter housing and so the filter diameter is D = 25 mm. The distance between both ends of the filter housing was defined by 1.5 mm and 3.0 mm, respectively, referring to narrow and wide filter. The membrane was positioned in the centre of the housing. The diameter of inlet and outlet tube matches with the inner diameter of a Luer Lock adapter (d = 2.1 mm) and the length was chosen to obtain a fully developed flow at the entrance of the filter housing. Since the filter consists of a radial symmetry and the flow is expected to be laminar, only one sixteenth of the filter is considered to reduce computational cost.

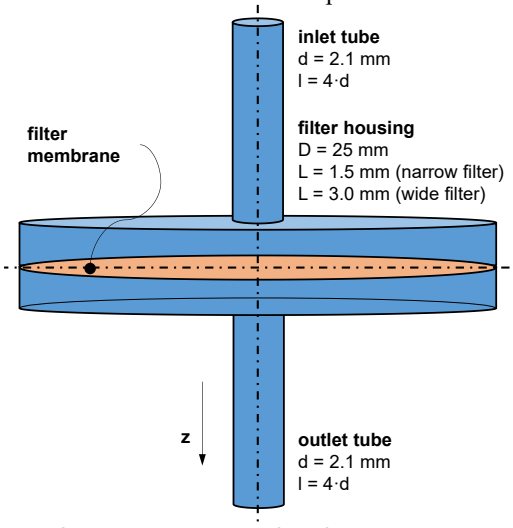

Figure 1: Schematic illustration of the filter w ith geometrical parameters

2.2 Numerical model

Since filter membranes have a thickness well below 1 mm the porous properties were modelled by a porous jump condition using ANSYS Fluent (Ansys Inc., Canonsburg, Pennsylvania, USA). This boundary condition approximates the membrane by an 1D mathematical model solving Darcy´s Law. The following parameter set was used to define the permeability of the filter membrane by using the porous jump condition: permeability $\alpha = 1.58 \cdot 10^{-11}$ m^2 and thickness of the membrane $\Delta m = 135$ µm.

As inlet condition a flow rate Q* = 2.5 ml/min was defined. This flow rate exceeds the recommended flow rate for long-term infusion by a factor of 2 to create a worst case scenario from a fluid mechanical point of view. At the outlet the pressure was set to p = 0 Pa. The calculation were conducted with distilled water at room temperature as medium given a viscosity of $\eta = 0.001$ mPa s.

2.3 Evaluation of filtration performance

For better comparison the velocity was normalized by the mean velocity resulting from the given flow rate Q* and membrane diameter D. Flow rate Q(r) and the radius r were normalized by input parameters (Q* = 2.5 ml/min and R = 12.5 mm). To quantitatively evaluate the filtration performance and, in particular, to assess the influence of the flow onto the filter membrane, we accumulated the normalised flow Q(r)/Q* and the normalised filter area A(r)/A* as a function of the filter radius r.

To illustrate evaluation approach, the following two theoretical examples are introduced: Hagen-Poiseuille inflow and uniform inflow. In Figure 2 the normalized velocity, the accumulated percentage of the filter area A/A* and flow rate Q/Q* are plotted as a function of the normalized filter radius r/R.

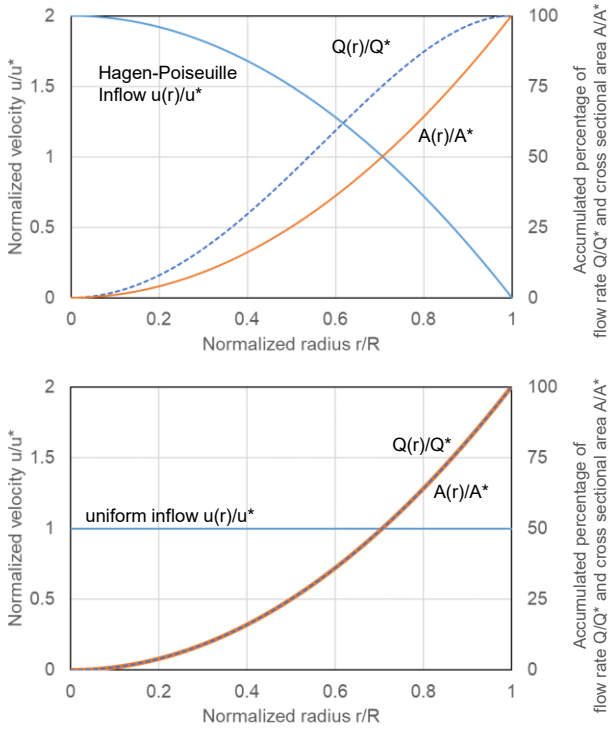

Figure 2: Velocity distribution u(r)/u* and accumulated percentage of normalized flow rate Q(r)/Q* and filter area A(r)/A* of a fully developed Hagen-Poiseuille flow (top) and uniform flow (bottom)

The uniform inflow could serve as theoretical best case in terms of membrane inflow. Here, the accumulated flow rate Q/Q* equals the accumulated filter are A/A*.

3 Results

Figure 3 illustrate the flow distribution inside the filter housings.

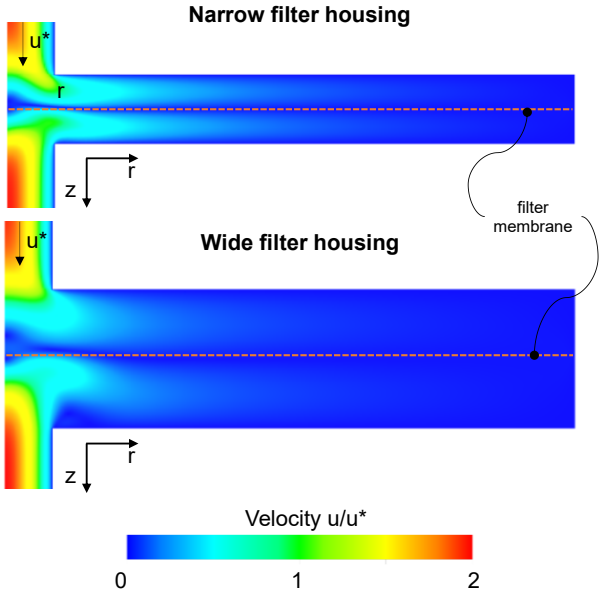

Figure 3: Velocity distribution inside the narrow filter housing (top) and inside the wide filter housing (bottom). Note: The entrance length is clip for this illustration.

It can clearly be seen that the velocity in the filter housing is well below the velocity within the Luer Lock adapters due to the sudden expansion of the cross section (factor 11.9).

In figure 4, the w-component of the normalized velocity is plotted over the normalized filter radius. Furthermore, the accumulated flow rate Q as well as the accumulated area is plotted.

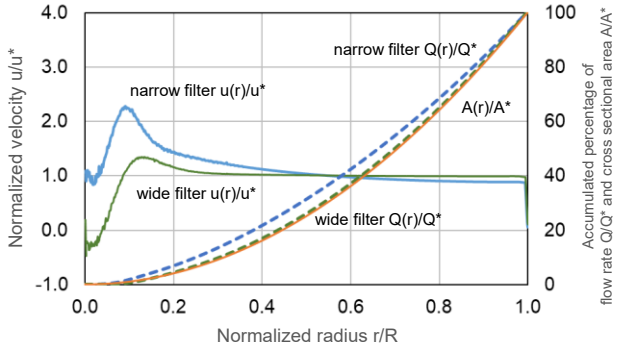

Figure 4: Velocity distribution and accumulated percentage von flow rate Q and cross sectional area A of a fully developed pipe flow

For both filter variants the velocity is low at the centre of the membrane despite the central inflow and increase to a maximum value. With increasing radius the velocity converge to the mean velocity value resulting in a highly homogeneous inflow of the membrane in particular for the wide filter housing. In this case, more than 92% of the membrane area is applied within a range of 5% of the mean velocity.

4 Discussion

Numerous studies have shown that in-line filters can significantly reduce particle contamination during infusion therapy and thus potentially prevent complications in patients. Our numerical analysis has shown that the filter housing has an influence on the inflow to the membrane. Nevertheless, both filter housings are already characterized by a very homogeneous inflow. A reasonable explanation could be the low flow velocity (mean velocity $8.6 \cdot 10^{-5}$ m/s) resulting in a Reynolds number of $Re > 1$ by utilizing the gap between filter housing and membrane as characteristic length. Further investigations should focus on large filter housings ($D > 50$ mm) due to the expected increasing influence of the filter housing with expanding filter diameters. Optimising the flow mechanics of the filter housing would significantly increase the performance of the filters in order to make their use even more effective.

It should be noted that the fluid used does not contain any particles, so the results show the initial velocity distribution of the flow. It is assumed that in the application case the membrane will clog during the process, which will influence the flow field. Future simulations should take this effect into account.

Author Statement

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Conflict of interest: JR, PC and DF are employees at RoweMed AG - Medical4 Life. The authors state no conflict of interest.

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