Numerical simulation of the flow field in pump intakes by means of Lattice Boltzmann methods

A Schneider, D Conrad and M Böhle
Institute of Fluid Mechanics and Fluid Machinery, Faculty of Mechanical and Process Engineering, Technical University Kaiserslautern, Gottlieb Daimler Strasse, 67663 Kaiserslautern, Germany
E-mail: andreas.schneider@mv.uni-kl.de

Abstract. Lattice Boltzmann Methods are nowadays popular schemes for solving fluid flow problems of engineering interest. This popularity is due to the advantages of these schemes: For example, the meshing of the fluid domain can be performed fully automatically which results in great simplicity in handling complex geometries. In this paper a numerical scheme for the flow simulation in pump intakes based on a Lattice Boltzmann large eddy approach is presented. The ability of this scheme to capture the flow phenomena of the intake flow at different operating conditions is analysed. For the operational reliability and efficiency of pumps and pump systems, the incoming flow conditions are crucial. Since the efficiency and reliability requirements of pumps are rising and must be guaranteed, the flow conditions in pump intakes have to be evaluated during plant planning. Recent trends show that pump intakes are built more and more compact, which makes the flow in the intake even more complex. Numerical methods are a promising technique for conducting flow analysis in pump intakes, because they can be realised rapidly and cheaply.

1. Introduction
Pump intakes, or simply called intakes, are hydraulic structures to withdraw water from open water (e.g. reservoirs or rivers). Application of intakes can be found for example in industrial plants or waste water stations. These hydraulic structures consist at least of an approach channel, which leads the water for withdrawing to one or more pumps (see Figure 1). For flow control, additional devices, like floor and sidewall splitters, can be included. The flow inside of pump intakes is generally very complex and contains commonly many coherent structures. If such vortex structures occur in the vicinity of the pump, this can lead to unacceptable inflow conditions for the machine, which have consequences such as loss of efficiency, vibrations or uneven impeller loading.

The vortices are classified, according to the location where they originate, as free surface or subsurface vortices. Subsurface vortices can develop from the side walls, the back wall or from the floor. Furthermore the flow field has been observed to be highly unsteady and the vortices to be intermittent and meandering. According to [1] and [2], free surface and subsurface vortices can be classified into different types, depending on vortex strength. The classification of free surface vortices respectively subsurface vortices is shown in Figure 2 and Figure 3. The vortex core develops more distinctly with increasing vortex strength or classification type. For free surface vortices the classification starts with a swirl of the surface (type 1) and extends to an air entraining vortex (type 6). The classification of the subsurface vortices ranges from a weak swirl (type 1) to a vortex with a
vapour, cavitating core (type 4). According to state of the art criteria there are only free surface vortices of type 1 and 2, respectively no subsurface vortices acceptable in operation [2].

![Figure 1. Pump intake geometry and main geometrical parameter](image1)

![Figure 2. Classification of free surface vortices [2](image2)]

![Figure 3. Classification of subsurface vortices [2](image3)]

The flow field in pump intakes depends on the geometrical parameters as listed in Figure 1 and the following dimensionless parameters: Reynolds number (Re), Froude number (Fr), Weber number (We) and circulation number (see e.g. [3] for details).

In the present paper numerical calculations of the flow field in a pump intake for different operating conditions and investigations of the flow topology are presented. The numerical results are obtained by a Lattice Boltzmann large eddy approach and are compared with measured flow data of the intake from [4].

The numerical analysis of pump intakes is requested, due to different limitations of physical model tests (see e.g. [2]) and its rapid and cheap utilisation. Some studies regarding the numerical analysis of pump intakes can be found in literature. A short review of the different approaches has been given recently by the authors in [5].

An advantage of the Lattice Boltzmann Method (LBM) which is especially useful in the context of intakes, is the possibility to handle complex geometries without manual meshing. This results in nearly no preprocessing effort. Another advantage is the high efficiency of the method in calculating transient
flows. The marginal preprocessing is perfectly suited to calculate various variants including lots of geometric details (e.g. splitters), as it is required for intake optimization.

2. Numerical investigations

The numerical investigations presented in this paper were carried out using the in-house tool “SAM-Lattice”, a CFD package based on the Lattice Boltzmann Method (LBM, for more details about “SAM-Lattice” see [5]). In contrast to classical Navier-Stokes solvers which are based on solving the macroscopic continuum equations, the LBM is a mesoscopic method, based on solving the Boltzmann equation in the continuum limit. For more details about LBM see e.g. [6].

The geometry of the analysed pump intake is shown in Figure 1. The intake structure is simple and consists of an approach channel with a free surface and an axial pump. There are no splitters or cleaning devices in this intake. In the laboratory model [4] the axial pump was simplified by a suction pipe with a suction bell. The dimensions of the intake are listed in Table 1. Three different operating points (OP) of the intake were analysed in [4]. These operating points assemble from two different flow rates of the pump (q) and two different submergences (S) of the pump bell. The operational and physical parameters for the different operating points are listed in Table 2.

| D [mm] | D/d | C/d | X/d | L1/d | L2/d | L/d | H/D |
|--------|------|------|-----|------|------|-----|-----|
| 100    | 1.5  | 1.0  | 1.1 | 0.65 | 0.85 | 25.86 | 6.0 |

| q [m³/s] | S/d | Re   | We   | Fr   |
|----------|-----|------|------|------|
| Operating Point 1 | 0.01667 | 1.3 | 2.12⋅10⁵ | 6189.53 | 0.2139 |
| Operating Point 2 | 0.01 | 1.3 | 1.27⋅10⁵ | 2228.23 | 0.1283 |
| Operating Point 3 | 0.01667 | 0.5 | 2.12⋅10⁵ | 6189.53 | 0.3448 |

The numerical model was set up to reproduce the experimental configuration of the laboratory model, but some assumptions were made to simplify the model: The simulations were performed as single phase flow with water. From an engineering point of view, this modelling is appropriate due to the state of the art criteria for acceptable vortices in intakes. But this assumption is only valid as long as movement of the free surface is small and the dynamics of air entraining vortices are comparable to single phase vortices. The free surface was assumed to be flat and treated as a frictionless wall due to the high Weber number (see e.g. [3]). The side walls, the back wall, the floor and the exterior and interior surface of the pump bell, respectively pipe, were treated as no-slip walls. The outlet of the fluid domain is at the end of the pipe, where a constant static pressure was specified. At the inlet of the fluid domain which is the open end of the intake channel, a flat velocity profile was specified. The velocity value at the inlet resulted from the corresponding flow rate and submergence of the operating point. To generate turbulent fluctuations at the inlet, a synthetic eddy method was used. For turbulence modelling a large eddy approach was used. As subgrid scale model the Smagorinsky model was chosen with a constant $C_{Smag}$ of 0.1. Within the Lattice Boltzmann scheme, a MRT model was used as collision model, due to its higher numerical stability (see e.g. [7]).

The time step for the simulations was chosen in the order of $6⋅10^{-5}$ s. Recording of transient results for instantaneous analysis and averaging was started after an initial period of $3⋅10^5$ time steps to obtain a statistically steady state solution. The result recording was performed for another period of $3⋅10^5$ time steps. The fluid domain was discretized by an equally sized grid with a spacing of 0.03·D. It resulted in approximately $7⋅10^6$ cells in the domain for submergence 1 and approximately $5⋅10^6$ cells for submergence 2.
3. Results

The calculated topology of the flow near the free surface at operating point 1 is illustrated by streamlines in Figure 4. The results are shown at four different instants of time. In the upper left picture one vertex that arranges between the pump and side wall 1 can be detected. A period later (see the upper right picture), no free surface vortex is visible, just some swirl remains. The two remaining pictures (lower part of the figure) show again one free surface vortex between the pump and side wall 1. The different snapshots demonstrate the change of the vortex location and its structure within time. In the experimental studies [4], one air entraining free surface vortex, located between pump and side wall 1, was detected. This vortex possessed intermittency and was visible for approximately 70% of the measurement time.

![Figure 4. Meandering and intermittency of free surface vortex at OP 1](image)

Figure 4. Meandering and intermittency of free surface vortex at OP 1

![Figure 5. Time-averaged surface streamlines at OP 1; bottom right: measured locations of free surface vortex [4]](image)

Figure 5. Time-averaged surface streamlines at OP 1; bottom right: measured locations of free surface vortex [4]

Time-averaged vortex structures in the intake at OP 1 are visualised by surface streamlines in Figure 5. The evaluation planes are close to the according physical boundaries. In the “free surface” plane, one dominant vortex between the pump and side wall 1 can be seen. This vortex and its position are corresponding to the experimental results [4], as shown in the bottom right picture of Figure 5. The time-averaged solution in all other planes shows in each case one dominant subsurface vortex. In [4] there are no details about subsurface vortices reported for OP 1. Thus, for these vortices no conclusions about accuracy of the numerical solution can be drawn.

The flow topology near the free surface at OP 2 is clarified in Figure 6, again for four different
Figure 6. Meandering and intermittency of free surface vortex at OP 2

Figure 7. Time-averaged surface streamlines at OP 2

Figure 8. Meandering and intermittency of free surface vortices at OP 3

Figure 9. Time-averaged surface streamlines at OP 3; bottom right: measured locations of free surface vortices [4]
instants of time. In contrast to OP 1, the flow rate in the pump dummy is reduced at these operating conditions. One vertex behind the pump which is intermittent and meandering can be detected.

Again, these results are according to the experimental studies [4]. It was reported that the air entraining vortex was visible for approximately 30% of the measurement time. The surface streamlines for the time-averaged vortex structures at OP 2 are shown in Figure 7 and are very similar to OP 1.

At operating point 3 the flow rate is according to OP 1, but the submergence is reduced. The flow topology near the free surface is different to the two other operating points, as shown in Figure 8. For some time two free surface vortices behind the pump are existent (see upper left picture). In the snapshots on the right part of Figure 8 only one of these vortices is present. The remaining picture shows no vortex at all. These phenomena are described in the laboratory experiment [4], too.

The vortex structures in a temporal average at OP 3 are illustrated in Figure 9 by surface streamlines. On the free surface, two vortices behind the pump can be detected time-averaged. The vortex positions are corresponding to the experimental results [4], as shown on the bottom right of Figure 9. A cavitating subsurface vortex (type 4) underneath the pump was reported for this operating point, through the experimental investigations. The time-averaged position of the calculated floor vortex corresponds with the measured area of this cavitating vortex (see Figure 9). The time-averaged solution shows one dominant subsurface vortex on each side wall plane. On the back wall, no dominant subsurface vortex can be identified.

4. Summary and conclusions
The flow field in a pump intake for different operating points was calculated with a Lattice Boltzmann large eddy approach. In this intake, depending on the operating point, many different vortex structures with transient behaviour appear. The CFD solution for all considered cases showed very good agreement with measurement data and flow observations. It was feasible to reproduce the different vertices in the intake by the CFD scheme. Furthermore, the transient features like meandering and intermittency of vertices were captured.

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