VISUALIZING DYNAMIC FLOW TRANSPORT OF A CENTRIFUGAL PUMP

M. OTTO[1,c], A. KUHN[1], W. ENGELKE[2], H. THEISEL[1]

[1] Institute for Simulation and Graphics, University of Magdeburg, Magdeburg, Germany
[2] King Abdullah University of Science and Technology (KAUST), Saudi Arabia

[c] Corresponding author: Tel.: +49391/6711349; Fax: +49391/6711164; Email: matotto@isg.cs.uni-magdeburg.de

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Introduction: In this work we present our results for applying specially designed time-dependent flow visualization methods to a simulation of a centrifugal pump. The simulation has been performed on a high-resolution grid (Figure 1) for 80 time steps using three turbulence methods (SAS, DES, SST [1]) with special focus on the analysis of the so called *rotational stall* phenomenon. This causes large areas of recirculation and significantly affects the efficiency and life time of the device. We provide a comparative visual analysis using common local vortex detectors as λ_2 and the Q criterion, and recent local methods as Sujudi & Haimes [2], and cores of swirling particle motion [3]. Local methods are shown to be insufficient to represent the functional impact and structural importance of the relevant features over time. To efficiently visualize stall cells we applied a set of global and time-dependent measures to convey size, spatial structure and temporal evolution of important transport effects and large-scale turbulent flow structures. Our analysis provides qualitative statements about the application of Lagrangian methods as FTLE [4], integral pressure, arc length of path lines and texture advection (Figure 1) revealing recirculation zones and blocked channels.

Introduction

Analyzing the flow behavior in turbo machinery represents a challenging topic for visualization. Due to increasing complexity of data and underlying flow behavior, direct interpretation of the results of simulations or measurements usually is not possible and requires further processing and visualization of the results. Using this to understand the underling motion process allows for a in depth insight into the creation and temporal development of physical effects during operation. Suitable approaches may also give rise to structural improvements or optimization of functional design. In this work we will present our results for applying a set of traditional and specially designed visualization methods to the high resolution simulation of a centrifugal pump [1] as illustrated in Figure 1. The given data set was part of the IEEE visualization contest in 2011 [7]. The data set itself consists of an inflow region, where fluid is led into the machine, a transport area consisting of five diffuser blades and corresponding channels and 12 outlet tubes. The flow in this data set was simulated on a dense irregular grid using three different turbulence models namely Scale-Adaptive Simulation (SAS), Detached Eddy Simulation (DES) and Shear Stress Transport (SST), while further details are described by Lucius [1]. Every turbulence model is given with 80 time steps which corresponds to one complete rotation of the impeller geometry. The underlying grid consists of approximately 6.5 Million hexahedral cells and 6.7 nodes. Besides, the pump was simulated using a part load setting below optimal working conditions. In this case, the pump throughput significantly decreases due to an physical phenomenon denoted as *rotating stall*. The rotating stall develops as small vortex structures at the tip of the impeller blades and creates large areas of dynamic recirculation within the separate diffuser channels. Backflow regions create a asymmetric load balance among the pump and drastically reduce its life time and efficiency for those settings. Hence, the primary goal in this work is to find suitable visualization methods to describe and analyze the development and effect of the rotating stall effect.

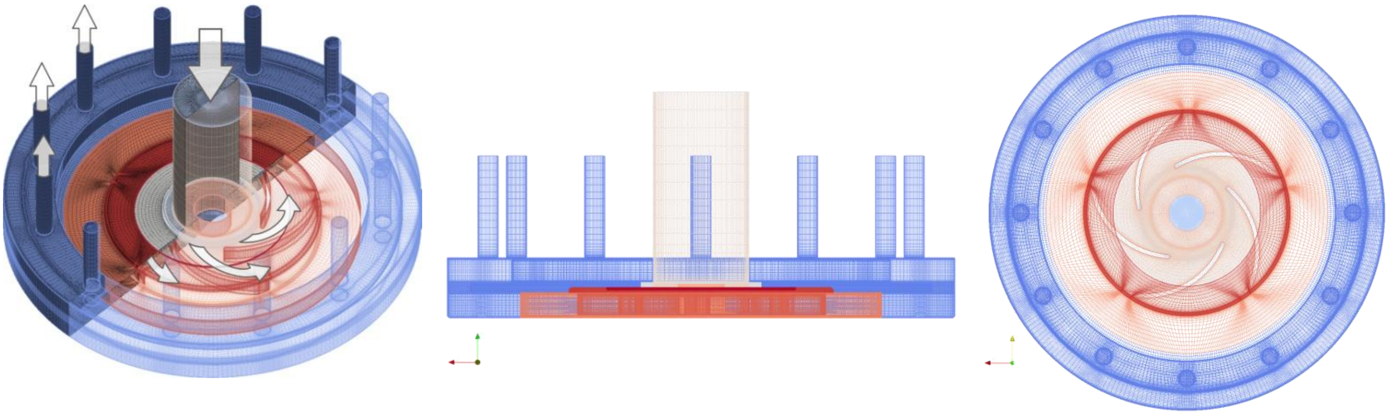

Figure 1: The left image shows the functional parts of the pump together with principle flow directions. The remaining images show side and top view with outlet and impeller sections of the transport area.

Local Approaches

Traditional methods mainly focus on the local detection of vortices within the flow. Two of the most well known methods are the Q [6] and λ_2 [5] criterion. Both methods are physically motivated and describe local vortex regions based on the rotation behavior encoded in the local spatial derivatives of the velocity field. They are both defined by means of level sets in the resulting scalar fields. For the λ_2 field we are interested in iso-levels larger than 0, for Q all levels smaller than a given iso-value. More recently, two methods have been proposed considering higher order derivatives and temporal derivatives of the flow, namely Sujudi & Haimes [2] and cores of swirling particle motion [3]. Both methods result in vortex core lines to describe the center of the vortex area. A comparative overview of all methods applied to the pump data set is illustrated in Figure 3.

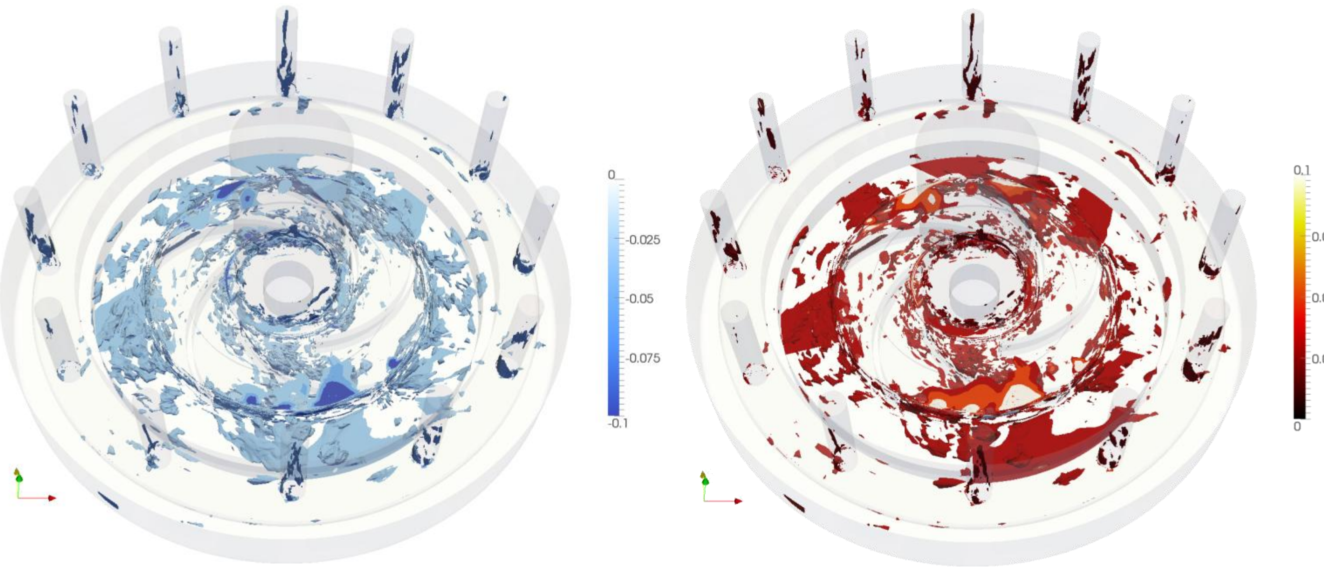

Figure 2: The image shows the λ_2 (left) and Q criterion as 3D iso-surfaces for the SAS model. The resulting structures are delicate and complex due to the high degree of turbulence in the velocity field. Further, they only describe one single time step ($t_0 = 0$), while a structural overview requires the consideration all time steps.

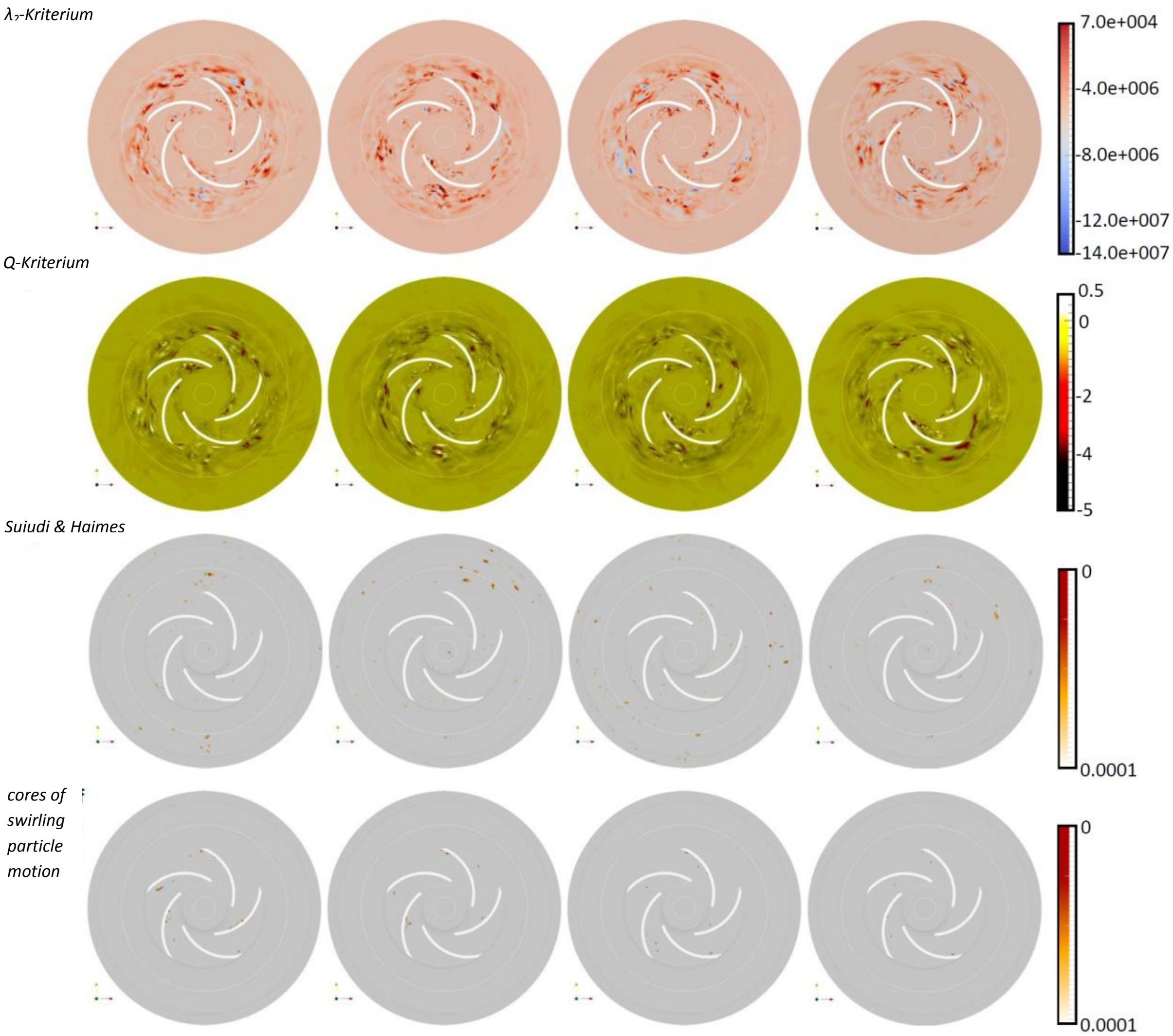

Figure 3: Comparative overview of different vortex criteria for the SAS Model (time steps 0, 25, 50 und 80). λ_2 vortices are defined as dark red iso-levels, Q as dark yellow regions. The last two criteria define binary maps, where dark spots mark potential vortex core line positions.

Global Approaches

In contrast to local methods, global approaches use time-dependent particle trajectories defined over a finite-time interval to describe the unsteady motion behavior. As illustrated in Figure 3, local methods only provide limited insight into the overall flow structure. Especially the notion of backflow events or evolution of features over time becomes hard to track with purely local approaches. Hence, we present a set of basic global methods, that allow for improved insight into the behavior of particles in close relation to the rotating stall phenomenon. The direct visualization of time-dependent particle trajectories or path lines encoding upward and downward moving flow portions is presented in Figure 4.

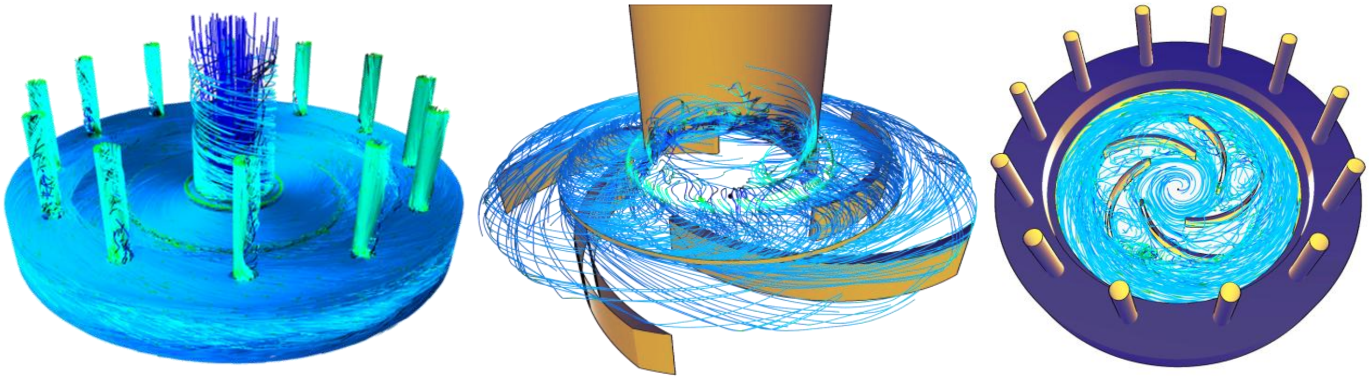

Figure 4: Path line visualization of particle trajectories for all 80 time steps. Color encodes the magnitude of the particle movement in z direction, while cyan indicates particles moving upwards, and dark blue particles moving downwards.

One popular approach to analyze the separation behavior of neighboring trajectories is the Finite Time Lyapunov Exponent (FTLE) [4]. Formally, FTLE is based on the flow map $\phi_{t_0}^{t_0+T}$ that defines the motion of particles for every location $\boldsymbol{x}$ starting at a time t_0 over a time interval T. Then the Cauchy-Green deformation tensor is defined as follows:

$$\nabla = \left(\frac{d\phi_{t_0}^{t_0+T}(\boldsymbol{x})}{d\boldsymbol{x}}\right)^{*} \cdot \frac{d\phi_{t_0}^{t_0+T}(\boldsymbol{x})}{d\boldsymbol{x}}$$

The final FTLE value is then defined as the normalized logarithm of the largest eigenvalue of this tensor:

$$\sigma_{t_0}^{T}(\boldsymbol{x}) = \frac{1}{|T|} ln\sqrt{\lambda_{max}(\nabla)}$$

The resulting FTLE scalar fields for one slicing plane in the lower part of the device are depicted in Figure 5. Although low FTLE values already indicate areas of backflow behavior, it is still hard to provide quantitative statements about the efficiency of the flow transport in the individual channels.

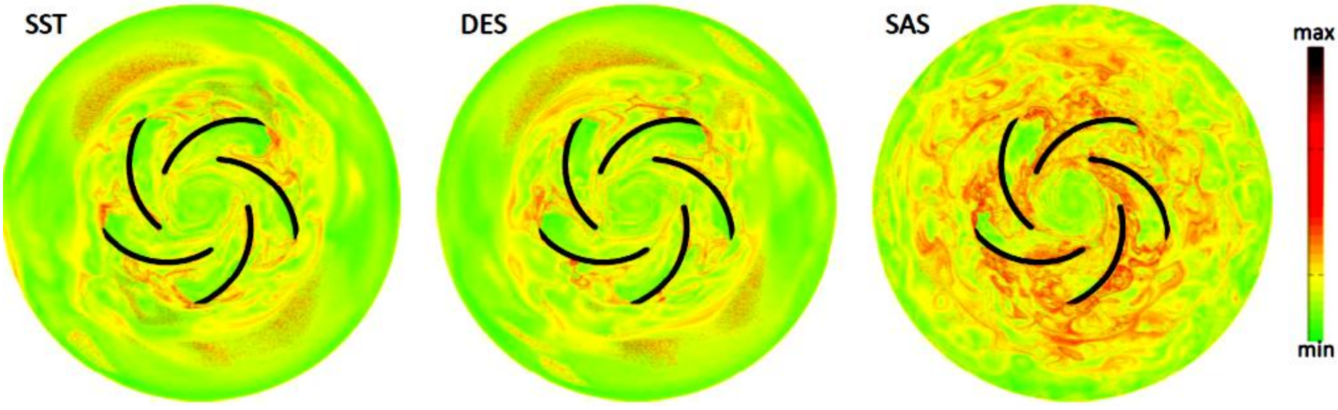

Figure 5: Comparative visualization of the FTLE field for all three simulation models with tau=80. Locally high FTLE values denote large particle separation, while low values indicate trajectories staying close over the considered time interval, which emphasizes potential backflow areas.

For this application regions of coherent flow speed are of special interest. This can be achieved visualizing the accumulated velocity in terms of path line arc length in Figure 6, that allows to identify areas of stagnating flow low velocity flow within the individual channels. The accumulated velocity can be expressed as follows:

$$l(\boldsymbol{x}) = \int_{t_0}^{\boldsymbol{T}} \| \boldsymbol{p}(\boldsymbol{x}, t) \|$$

where $\| \boldsymbol{p}(\boldsymbol{x}, t) \|$ denotes the Euclidean norm of a vector along one path line or particle trajectory.

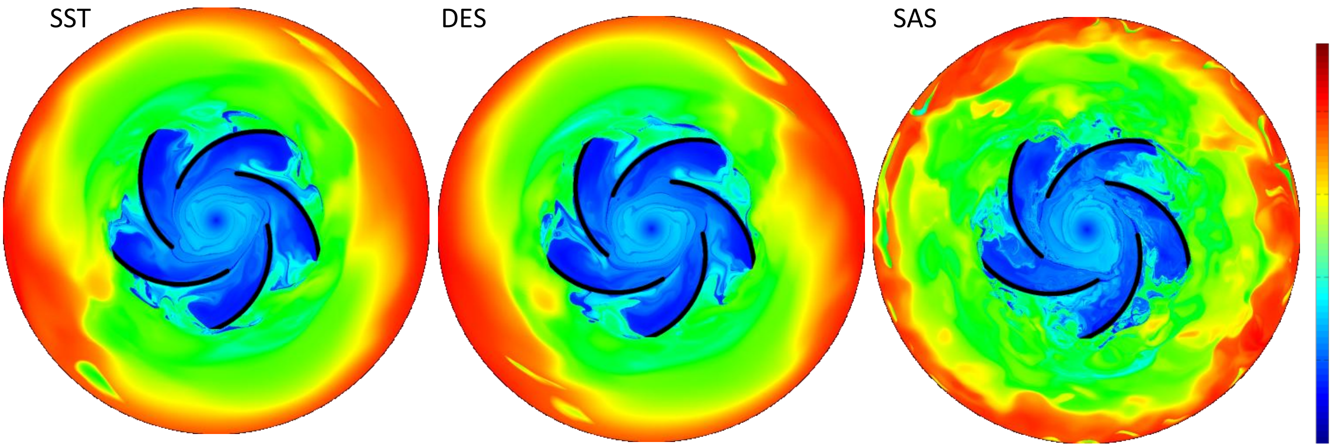

Figure 6: Comparative visualization of the accumulated velocity field for all three simulation models with tau=80. Locally low values denote regions of stagnating flow and lower particle velocities. This becomes especially apparent in the center of blocked channels.

Similarly, we can define the integrated pressure field using the local scalar pressure $\boldsymbol{s_p}$ defined over $\boldsymbol{x}$ in an integral fashion:

$$\dot{\boldsymbol{s}}_{\boldsymbol{p}}(\boldsymbol{x}) = \int_{t_0}^{\boldsymbol{T}} \boldsymbol{s}_{\boldsymbol{p}}(\boldsymbol{x}, t)$$

In combination with local information, such global measures further allow to identify regions of low accumulated pressure along one particle trajectory over the given time interval which is illustrated in Figure 8.

In addition to the evaluation of scalar measures along the particles trajectories, adding further knowledge about the structural properties of the pump in terms of a textured regions, allows to efficiently encode the flow transport behavior over the complete time interval. This can be achieved by considering an input volume texture $\boldsymbol{i}(\dot{\boldsymbol{x}})$ and use the propagated flow map position $\dot{\boldsymbol{x}} = \phi_{t_0}^{t_0+T}(\boldsymbol{x})$ to look up the color value after particle integration in the original texture. Integrating this regional information in forward direction throughout the flow compactly encodes which portions of the flow end up in which channels as illustrated in Figure 7.

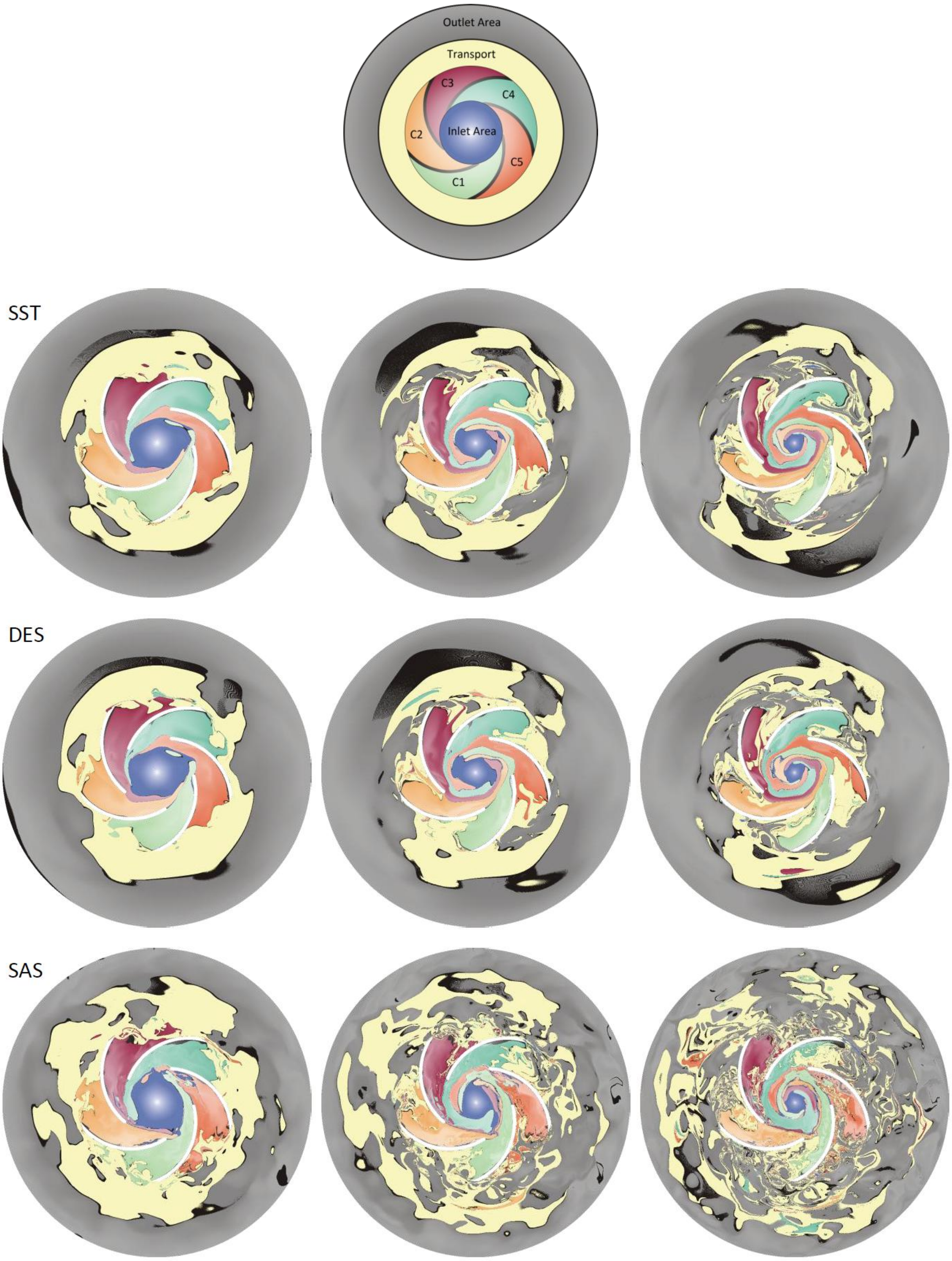

Figure 7: Using advection of a given input texture clearly shows the resulting transport into the channels after 20, 50, and 80 time steps. Using forward advection the visualization efficiently encodes which areas end up in a specific channel after the advection time.

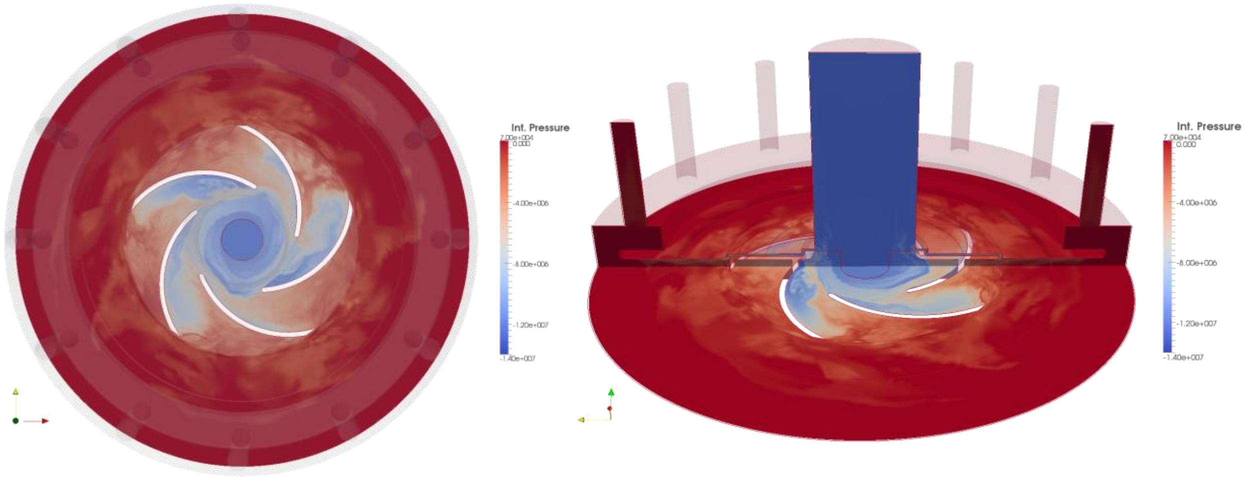

Figure 8: Integrated pressure for the SAS model over the complete temporal domain. Locally minimal regions (blue) indicate areas of recirculation and stagnating flow.

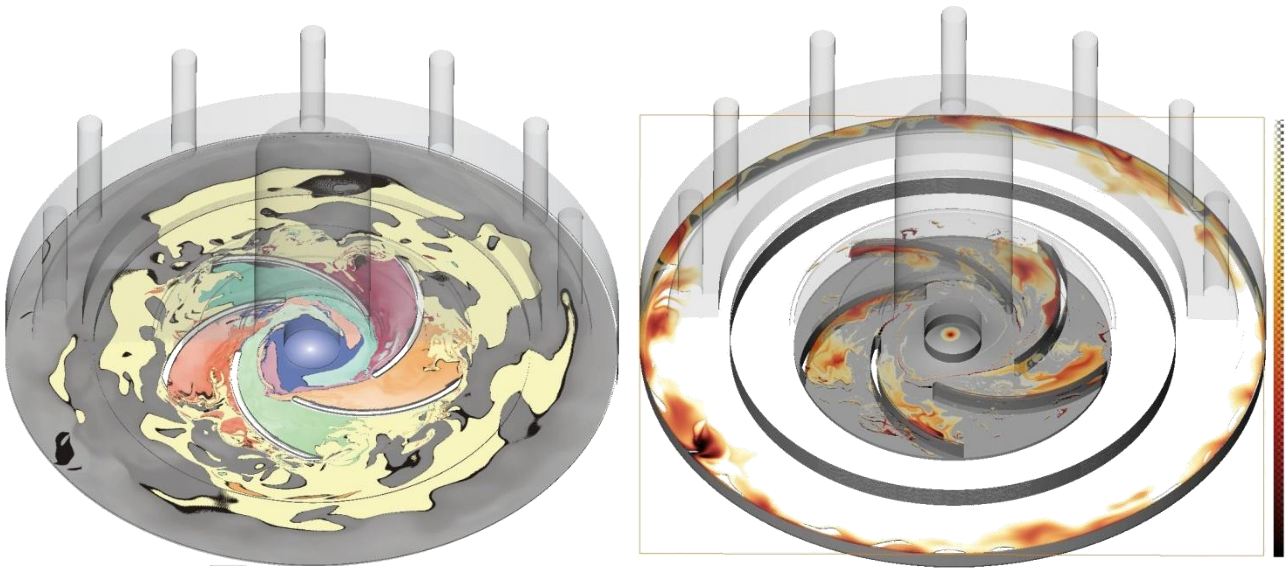

Figure 9: Both image illustrate two global measures in the geometric context of the pump. The left image illustrates the advected channels of the SAS model until time step 50. On the right side stagnating flow areas are emphasized, which effectively communicates blocked channels.

Conclusions

In this work we present a set of advanced integration-based methods to visualize the global transport behavior within a high-resolution centrifugal pump simulation. Due to the high degree of turbulence, classic local vortex detectors are less suited to capture the temporal development of the important flow structures within the pump. Further, they have to be evaluated and compared for every single time step individually.

We showed that global integration-based methods are well suited to improve comparability between different simulation models, while capturing the time-dependent flow behavior over a given time interval. Besides FTLE [4], the arc length measure and accumulated pressure are particularly useful to emphasize the impact and development of the rotating stall phenomenon, that is of special importance in this case. Using texture advection further emphasizes areas of recirculation, transport rates within functional areas over the respective time interval, as well as the distribution of the input flow among the separate channels.

Acknowledgements

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