THE IMPORTANCE TO CONSIDER ADVANCED FLUID PROPERTIES IN FLOW SIMULATION OF POSITIVE DISPLACEMENT MACHINES

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Simulation of positive displacement machines requires highly skilled engineers, use of advanced simulation tools and advanced simulation approach. The paper presents recent activities and progress on simulation of positive displacement machines – in particular, the axial piston pump and the radial hydraulic motor. Despite that these machines have been designed and produced for decades, there are still (design) features and phenomena not being investigated in detail or never being simulated. The simulation advancements mainly refer to the application of complicated kinematic motion, fluid properties, physics to consider as well as mesh and numerical algorithm techniques. In this paper, the focus is on modelling of advanced fluid material properties. Numerical approach has been performed by means of CFD within the environment of Siemens Simcenter Star-CCM+. The anticipation of cavitation has been possible by implementation of existing "full cavitation model".

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1 Introduction

In this very first part, let's unpack the term "positive displacement machine" step by step. Positive displacement principle states that the space required to generate flow rate during a function period is geometrically reduced (compressing period) and increased again (decompressing or suction period). The pressure to be applied is determined by the resistance that the actuator (e.g. cylinder, motor) must overcome. [1], [2], [3]

Displacement machines are hydraulic machines (i.e. pumps, motors) in which hydrostatic power is transferred downstream of the positive displacement principle. In terms of the operating principle, a distinction is made between rotary type (rotating components) and reciprocating type (linear motion). In the rotary machines the transport process takes place in a circumferential direction and is characterized by the size 2π. On the other hand, reciprocating machines work with the displacement units (e.g. pistons) performing a linear movement. [1]

Figure 1: Example of reciprocating (left) and rotary machine (right).
Source: own

Typical representatives of reciprocating machines are axial piston pumps, radial piston motors, diaphragm pumps, plunger pumps etc. Typical representatives of rotary machines are gear pumps, lobe pumps, vane pumps, screw pumps etc.

1.1 Axial piston pump

An axial piston pump is a type of positive displacement machine that uses a series of pistons arranged in a circular pattern within a cylinder block (or rotor); see Figure 2. These pistons move in a direction parallel (axial) to the axis of rotation of the cylinder block. Axial piston pump exists as fixed (constant flow rate) or variable displacement (swash plate angle can be changed, varying the stroke of the pistons and adjusting the flow rate).

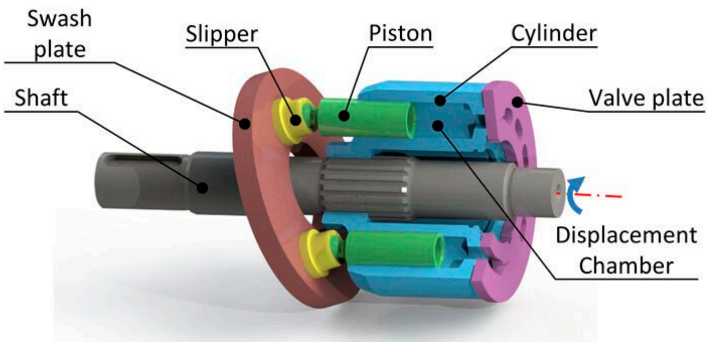

Figure 2: Rotating group of axial piston pump.
Source: [4]

1.2 Radial piston motor

Radial piston motor is a type of positive displacement machine that converts hydraulic energy (i.e. fluid pressure) into rotational mechanical energy (i.e. torque). It gets its name because the pistons are arranged radially around a central crankshaft or a cam. Two main types of radial piston motors exist: crankshaft and cam ring type (or multi-lobe cam type). The latter consists of stationary housing, rotating cylinder block, radial pistons arranged in a circle inside the rotor and multi-lobe cam ring that stays fixed (figure 3) [7].

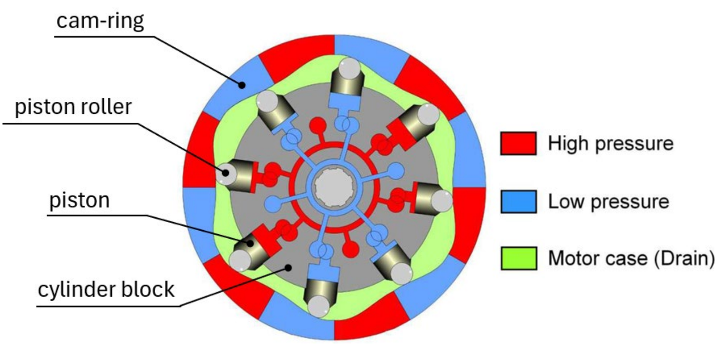

Figure 3: Typical cross-section view of radial piston motor.
Source: own

2 Physics to consider

Positive displacement machines are complex products – not just from component point of view, but also from physics point of view. Several different physical phenomena appear in such machine: starting from solid mechanics (e.g. solid stress, tribology, materials …) further to fluid mechanics (e.g. fluid properties, turbulences, cavitation …) and more.

Implementation of those phenomena into physical model(s) is of course not an easy task and knowledge from different physical domains need to be merged.
For this investigation purposes, one of the most challenging physical domains will be introduced hereafter – cavitation phenomena.

2.1 Cavitation phenomena

Cavitation is the phenomenon where vapor cavities (which are small and mostly liquid-free zones), known as bubbles or voids, are generated in a liquid due to the imbalance of the local dynamic forces. This usually occurs when a liquid is subjected to rapid changes of pressure under isothermal conditions. An example: if the pressure falls below a threshold (vapor saturation pressure), the liquid will rupture and form vaporous cavities, while the voids would implode (bubbles collapse) and generate intense shock waves when the vapor bubbles are subjected to pressure higher than the threshold pressure (Figure 4) [6].

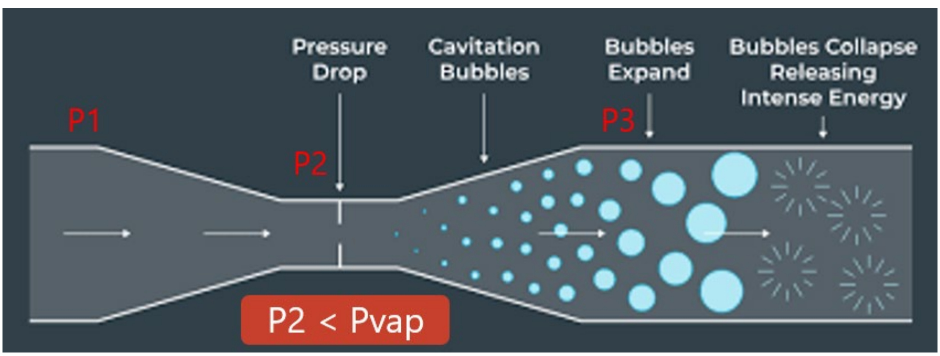

Figure 4: Cavitation resulting from a drop of pressure.
Source: [9]

Two principal types of cavitation exist: vaporous and gaseous. Vaporous cavitation is a process that takes place if the bubble grows explosively as liquid rapidly changes into vapor; this situation occurs when the pressure level goes below the vapor pressure of the liquid. Gaseous cavitation, on the other hand, is a diffusion process that occurs whenever the pressure falls below the saturation pressure of the non-condensable gas dissolved in the liquid.

Physical model for cavitation) bubble

A typical physical model for single (cavitation) bubble is shown on Figure 5.

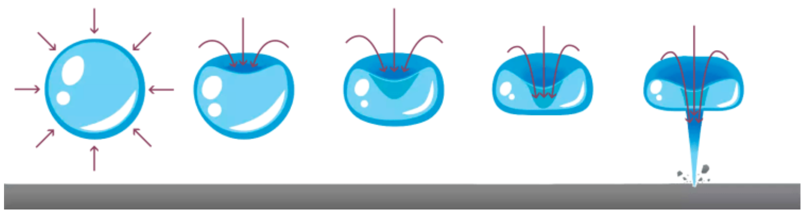

Figure 5: Collapse of single cavitation bubble.
Source: [14]

In most cases, cavitation is an undesirable phenomenon, causing significant degradation in the performance (e.g. reduces mass flow rates, lower head rise in pumps, load asymmetry, vibration, and noise). Cavitation also causes physical damage to a device due to bubble impact on surfaces (very right stage on figure 5), which can ultimately affect structural integrity.

Cavitation is a very complex phenomena and its details are still under deep investigation. Huge progress in understanding single cavitation bubble collapse has been made within the last decade (mainly thanks to deeper and sophisticated visual examination). [10], [11], [12], [13]

2.2 Difference between cavitation and boiling

Boiling is a phase change at constant pressure and variable temperature; cavitation on the other hand is a phase change at constant temperature and variable pressure (Figure 4).

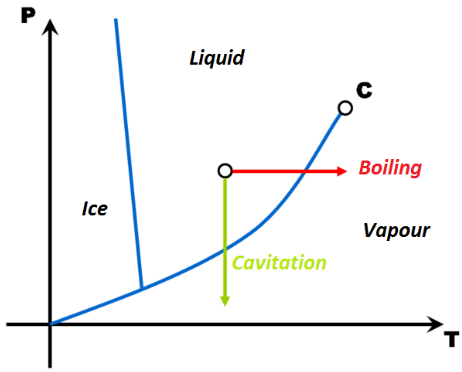

Figure 4: Boiling versus cavitation.
Source: own

Fundamentally, both cavitation and boiling are the evaporation and condensation process between liquid and vapor phases. However, the mechanisms that trigger the phase changes are different. Cavitation is predominately caused by mechanical effects which are the sharp pressure changes in fluid systems. Boiling is due to thermal effects that raise the vaporization pressure of a liquid above its local ambient pressure to cause the phase change from liquid to vapor [5].

3 Numerical techniques

Knowing and understanding appropriate physics is the very first and essential step. Then, the next challenging step is to implement physics into numerical code. Not every physical model could be efficiently coded or significant skills in programming is needed. Implemented physical model of cavitation and mesh techniques are briefly explained hereafter.

3.1 Cavitation model

For this study purposes, implementation of advanced fluid properties has been of significant importance. Numerous models are available within many scientific papers and publications. However, not many of them are suitable for 3D CFD purposes (e.g. [16]) due to the lack of numerical robustness, stability, performance etc. Hereafter, “full cavitation model” from Singhal et al. [15] has been used and implemented into CFD code within Siemens Simcenter Star-CCM+.

The basic approach consists of using the standard viscous flow (Navier-Stokes) equations for variable fluid density and a conventional turbulence model (e.g. k-ε model). The fluid density is a function of vapor mass fraction f, which is computed by solving a transport equation (1) coupled with the mass and momentum conservation.

$$\frac{\partial}{\partial t}(\rho f) + \nabla \cdot (\rho \vec{V} f) = \nabla \cdot (\Gamma \nabla f) + R_e - R_c \tag{1}$$

The source terms R_e and R_c denote vapor generation (evaporation) and condensation rates and can be functions of flow parameters (pressure, flow characteristic velocity) and fluid properties (liquid and vapor phase densities, saturation pressure, and liquid-vapor surface tension). The above formulation employs a homogenous flow approach and therefore does not consider two-phase (two-fluid) flow.

The primary focus is on proper account of bubble growth and collapse. In a flowing liquid with zero velocity slip between the fluid and bubbles, the bubble dynamics equation is derived from the generalized Rayleigh-Plesset equation.

$$\mathfrak{R}_B \frac{D^2 \mathfrak{R}_B}{Dt^2} + \frac{3}{2}\left(\frac{D\mathfrak{R}_B}{Dt}\right)^2 = \left(\frac{P_B - P}{\rho_l}\right) - \frac{4\nu_l}{\mathfrak{R}_B}\dot{\mathfrak{R}}_B - \frac{2S}{\rho_l \mathfrak{R}_B} \tag{2}$$

Equation (2) provides a physical approach to introduce the effects of bubble dynamics into the cavitation model. In fact, it can be considered as an equation for void propagation and, hence, mixture density.

The working fluid is assumed to be a mixture of liquid, liquid vapor and non-condensable gas (NCG). The calculation of the mixture density is defined as

$$\frac{1}{\rho} = \frac{f_v}{\rho_v} + \frac{f_g}{\rho_g} + \frac{1 - f_v - f_g}{\rho_l} \tag{3}$$

where $\rho_g, \rho_v, \rho_l, f_v, f_g$ refer to the NCG density, vapor density, liquid density, mass fraction of vapor and mass fraction of NCG, respectively.

The main unknowns are p_{vap} (vapor saturation pressure) and f_g. Their variation depends on fluid type and its quality and can be significant [16]. The model has been validated on several different cases.

Besides that, this cavitation model exhibits the following characteristics:

- Can be applied to any geometric system (3D, 2D planar, or 2D axisymmetric), all grid cell types and arbitrary interfaces are supported;
- Concurrent use of the turbulence, grid deformation and/or structures solution modules are fully supported;
- Flow is assumed isothermal and fluid properties are taken as constant at a given temperature for the entire flow domain;
- NCG mass fraction (f_g) is assumed to be constant in the flow field.

3.2 Mesh morphing

Many simulations that involve motion or geometry change require moving or deforming the mesh. Different deforming mesh methods (and their naming) exist, such as overset mesh, morphing, adaptive mesh refinement, general remeshing etc. The morpher motion allows to account for the effect of moving boundaries in a transient simulation. The morpher can be used, for example, to simulate the reciprocating motion of a piston in a cylinder - where the boundaries are not changing shape, but the mesh vertices must morph to accommodate the movement [17].

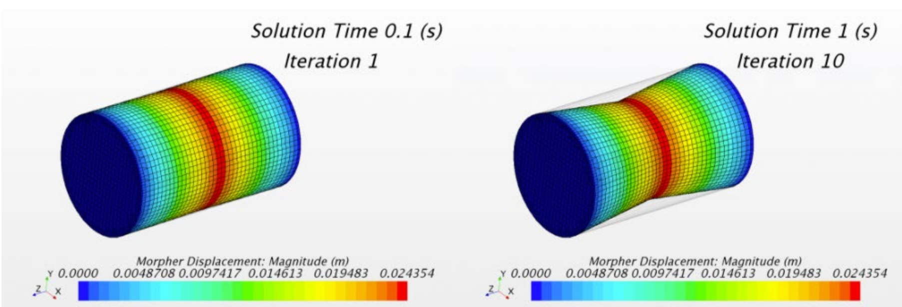

Figure 5: Cylinder with a contracting wall.
Source: [17]

The morphing motion in Siemens Simcenter Star-CCM+ redistributes mesh vertices in response to the movement of a set of control points, which can be considered as being a cloud of points overlaid onto the mesh domain. The displacement of a point can be set directly, or it can be calculated from the input of grid velocity, from which the displacement is calculated for a given time step.

3.3 Rigid body motion

Rigid body motion allows to model the motion of a rigid body in response to applied forces and moments. In a rigid body, the relative distance between internal points does not change. Therefore, it is sufficient to solve the equations of motion for the center of mass of the body (Figure 6).

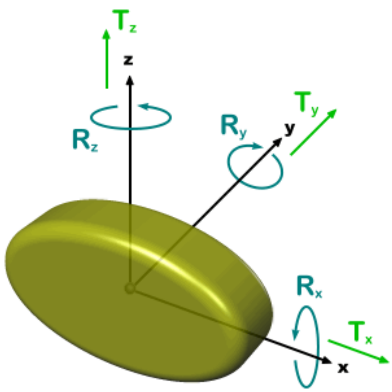

Figure 6: The motion of a 3D rigid body has 6 degrees of freedom.
Source: [17]

4 3D numerical model of the axial piston pump

The investigation refers to the flow analysis on pump PM10. The aim of this analysis is to evaluate pressure field in piston chamber for "full pump" model (i.e. all pistons are used). 3D view of the pump PM10 is depicted on Figure 7.

3D CFD model considers unsteady conditions, mesh morphing, realizable k-e turbulence model, passive scalar transport equations and user-defined equation of states (compressibility).

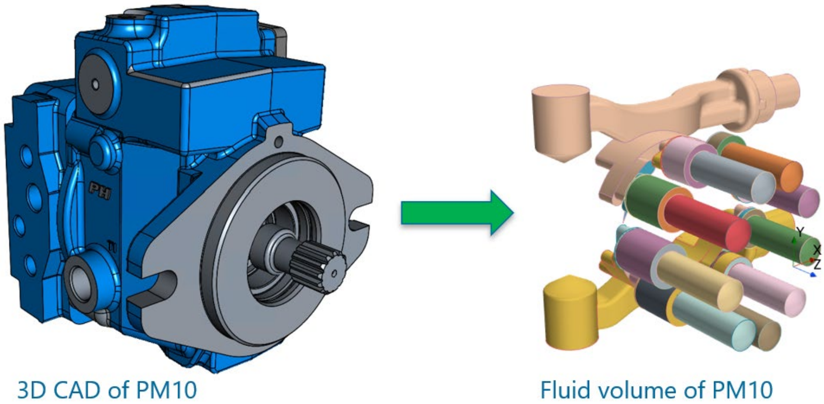

Figure 7: 3D CAD model (left) and fluid volume chambers (right).
Source: own

Flid volume has been meshed with polyhedral cells (where appropriate), hexahedral cells on areas of variable volume and with prisms next to boundaries. Contact/interface areas have been meshed with conformal mesh. Full 3D meshed fluid volume (rotating group and inlet/outlet chambers) is depicted on Figure 8.

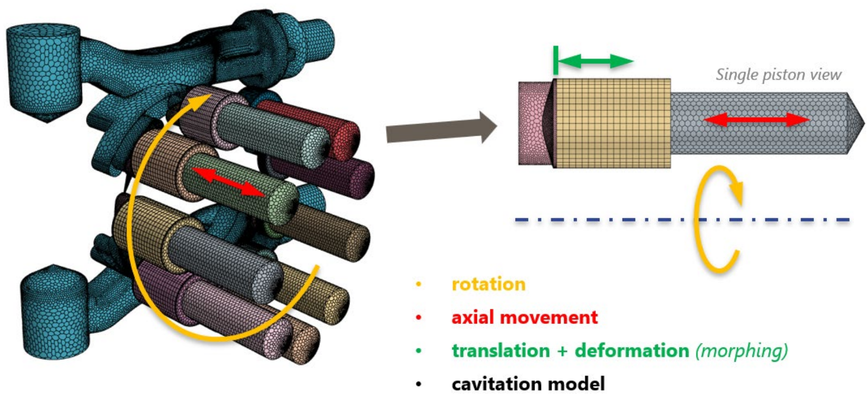

Figure 8: Mesh of fluid volume.
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Figure 9 depicts normalized piston velocities, used as boundary conditions. The curves have been obtained thanks to equation based parametric CFD model.

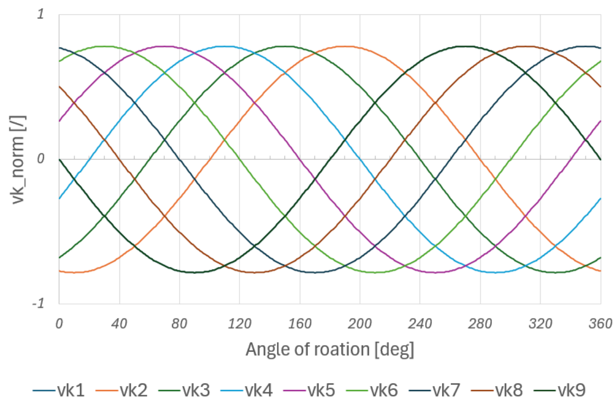

Figure 9: Imposed piston velocities.

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5 Results and discussions

Simulation has been defined for one full rotation (2π rad). During the rotation, several different physical quantities have been observed.

5.1 Piston chamber pressure

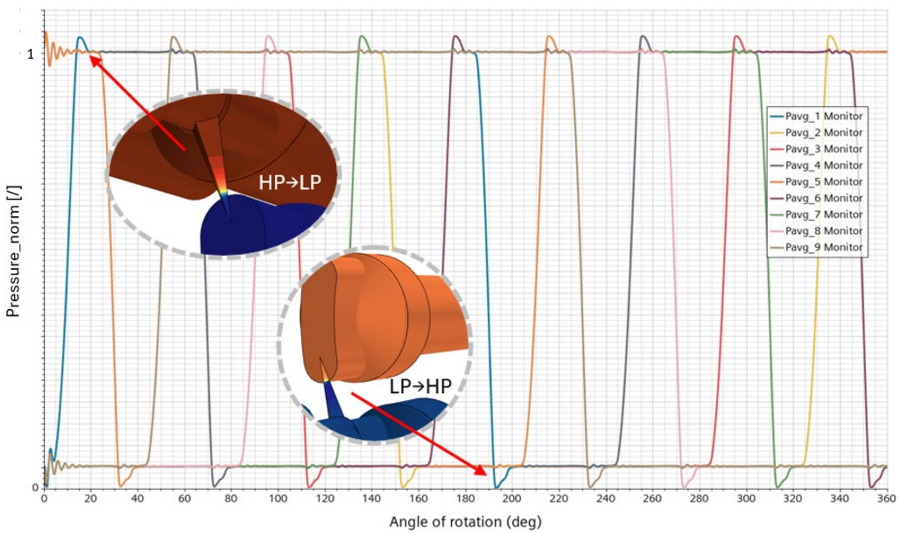

Figure 10: Normalized average piston chamber pressure.

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Piston chamber pressure (Figure 10) is a direct consequence of imposed piston velocity. A typical pressure pattern could be seen during one revolution. In the first part, there are some instabilities (i.e. oscillations) due to initialization. Then, each pressure spike (in terms of pressure under/overshoot) is a consequence of interface with high (HP) or low-pressure (LP) chambers.

Piston pressure force (in axial direction) is an integral value of pressure over the piton area. Corresponding curves have identical shape as for the pressure, so they are not shown here.

5.2 Piston tilting moment

Piston tilting moment (Mts) is depicted on Figure 11. Observing curve for piston #1, there is negative Mts in the first part of rotation. This is because piston chamber #1 is under high pressure (HP) and generated moment try to rotate in negative direction. It is opposite when the chamber is under low pressure (LP). The magenta curve depicts sum of all tilting moments (from all pistons chambers). One can sees that it is not constant and changes significantly during one revolution.

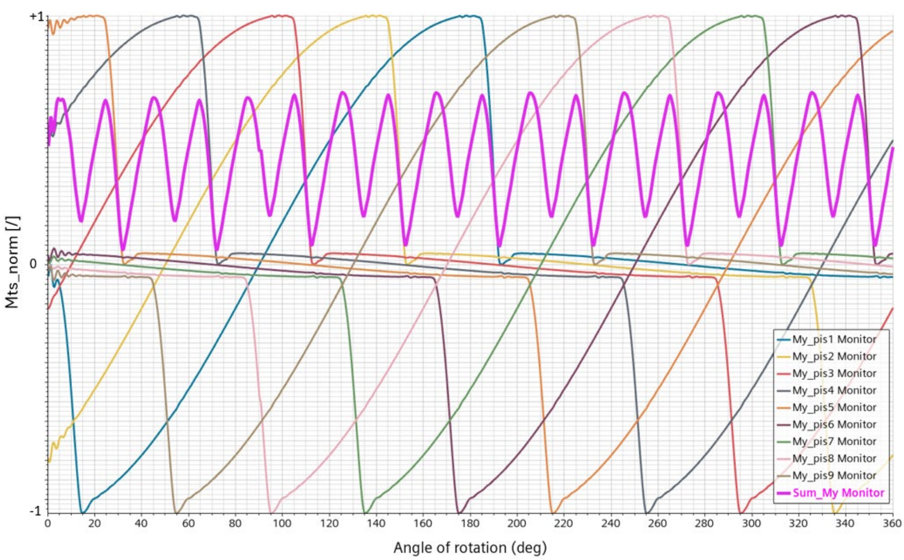

Figure 11: Normalized piston tilting moment Mts.

Source: own

5.3 Flow rate

Piston volumetric flow rate (VFR) could be seen on Figure 12. The very top and bottom curves refer to the total flow rate at the inlet and outlet ports. Total flow rates are not constant and change during the revolution. In addition, flow rate for each piston sees two local increase/decrease in flow rate (offset for π rad) due to beginning of the interface with high/low pressure zone or vice versa.

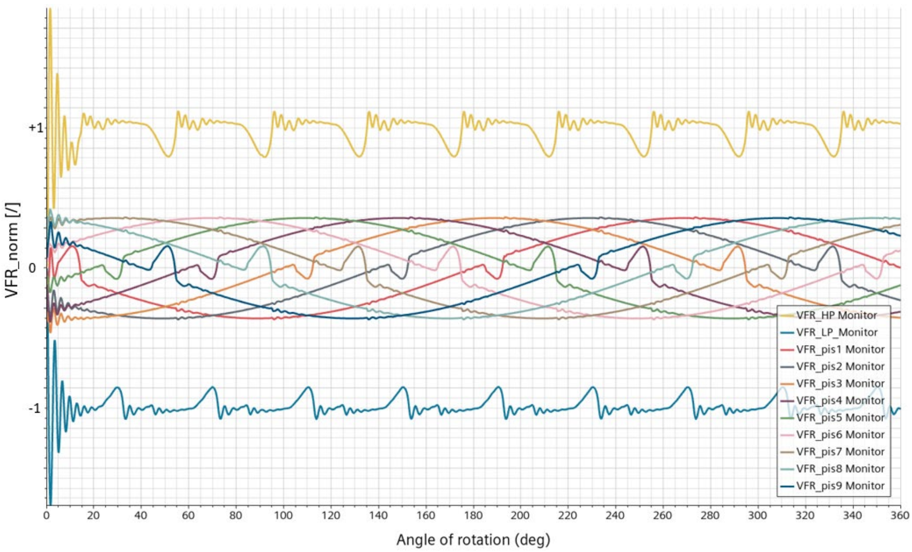

Figure 12: Normalized volumetric flow rate (VFR)
Source: own

6 Conclusion

Positive displacement machines are widely used in the engineering fields. Usually, such machines operate in a harsh environment and extreme conditions. Detailed understanding their functionalities is a key point for proper (robust) design, predicted service lifetime and finally, for customer satisfaction. Simulation-driven design can significantly decrease design cycle (lower the iteration loops), reduce experimental investigations and gain time to market. However, simulation of such machines requires advanced skills in numerical modeling. Although that these machines are presented on the market for decades, there is still lack of their detailed understanding.

In this study, numerical approach has been performed by means of computational fluid dynamic (CFD) within the environment of Siemens Simcenter Star-CCM+. The cavitation has been implemented into the CFD code in order to assess the potential cavitation areas. Results of flow analysis (e.g. piston chamber pressure, tilting moment on a swash plate etc.) enables better understanding of the key functionalities for such machines but also serve as design guidelines for engineers.The constructed numerical model opens the door for its further improvement, deeper investigation of axial piston pumps as well as its further deployment to the other type of positive displacement machine (i.e. hydraulic motor), produced by Poclain.

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