VII International Conference on Particle-Based Methods
PARTICLES 2021
P. Wriggers, M. Bischoff, E. Oñate, A. Düster & T. Zohdi (Eds)

NUMERICAL INVESTIGATION OF CHURNING LOSSES CAUSED BY THE OIL-PISTON INTERACTION WITHIN A CALENDER ROLL OF A PAPER MACHINE USING A PARTICLE-BASED SIMULATION METHOD

MARCUS BRITZ[*],
BETTINA GRASHOF[†], PATRICK WEGELE[†] AND HEIKO LINDER[†]

[*] J.M. Voith SE & Co. KG
St. Pöltener Straße 43
89522 Heidenheim, Germany
e-mail: Marcus.Britz@voith.com, www.voith.com

[†] J.M. Voith SE & Co. KG
St. Pöltener Straße 43
89522 Heidenheim, Germany
www.voith.com

Key words: paper machine, calender, MPS, Particleworks®, oil, churning loss.

Within the paper production process, certain surface properties of the paper web, e.g. smoothness and gloss, are produced or modified by so-called calenders. This paper machine device consists of several rolls, which apply high pressure and temperature on the paper web. Calenders exhibit large widths up to more than 10 m. Therefore, it is challenging to precisely adjust the required mechanical forces in order to apply a defined line load across the entire width of the paper web. By making use of Voith's Nipco technology, both line load and roll deflection are controlled by multiple pistons which can be individually adjusted. This is achieved by pressure oil injection. The piston works also as a hydrostatic bearing in such a way that a thin lubrication film is formed between the stationary piston head and the rotating roll shell. Additional oil is injected into the roll for cooling purposes.

Within this paper we present an industry-related approach to take advantage of present-day Moving Particle Simulation (MPS) methods. Hereto, we used the commercial software Particleworks® for a numerical investigation of the flow phenomena within a calender roll. The focus of our investigation were the churning losses caused by the interaction between the rotating oil and the mounted piston head. For this purpose, simulations of different oil volumes were performed.

The results show that the piston head has a clear impact on the flow field. Firstly, the oil is reflected in upstream direction, causing disturbances in the subsequent flow. Secondly, the oil which streams around the piston rod leads to the formation of a Kármán vortex street. Thirdly, a reduction of oil volume results in a reduction of the churning loss.

1 INTRODUCTION

Producing paper needs many process steps. A general setup of the entire paper production process can be taken from **Figure 1**. At the beginning of the proceeding, in the stock preparation, recycled paper and fresh fibers, so-called virgin fibers, are mixed with water in the pulper to create a fiber suspension, which is pumpable [1]. In the next process steps, the fiber suspension is screened and cleaned to remove dirt particles (sand, styrofoam, etc.). Finally, the refining takes place to improve paper quality such as tear strength of the paper. Subsequently, the cleaned furnish is brought onto the paper machine, in which it is dewatered. The first dewatering step takes place within the former and press section. The following thermal dewatering is realized in terms of heated steam cylinders within the dryer section. The produced paper is now rolled up at the reel section onto a metal spool to create a paper roll, which is called tambour. This is the final product of the paper machine, which can be used to perform further process steps such as calendering. Depending on the customer's needs, calendering can take place either after the paper machine (off-line) or within the paper machine before the reel section (on-line), as shown in **Figure 1**.

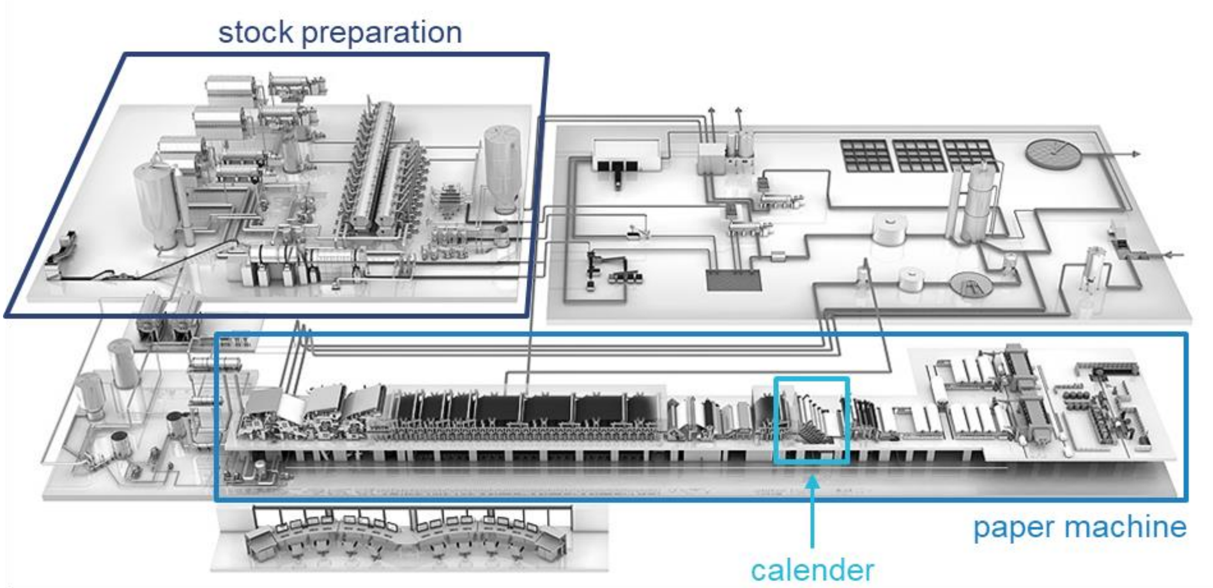

Figure 1: Typical setup of paper production process and localization of on-line calender within a paper machine.

Within the calender section, the surface properties of dried paper web can be modified. Typical surface properties are smoothness and gloss which are realized by applying high pressure and temperature on the paper. Often, this procedure is compared with the process of ironing clothes, whereby the processing steps and the ways of proceeding are similar. The calender can consist of several rolls to bring the required high pressure and temperature on the paper surface (so-called multi roll calender), see **Figure 2** (left). One roll includes multiple pistons along its machine axis. The high amount of pistons is necessary to adjust the required constant pressure along the entire paper web width to ensure uniform paper surface quality. At every single piston, oil is injected so that a thin oil film is created to lubricate the rotating roll and the stationary axle, see **Figure 2** (right). Additionally, the oil is used to adjust the required temperature. Hereto, the oil needs to be continuously cooled down in an external oil circuit.

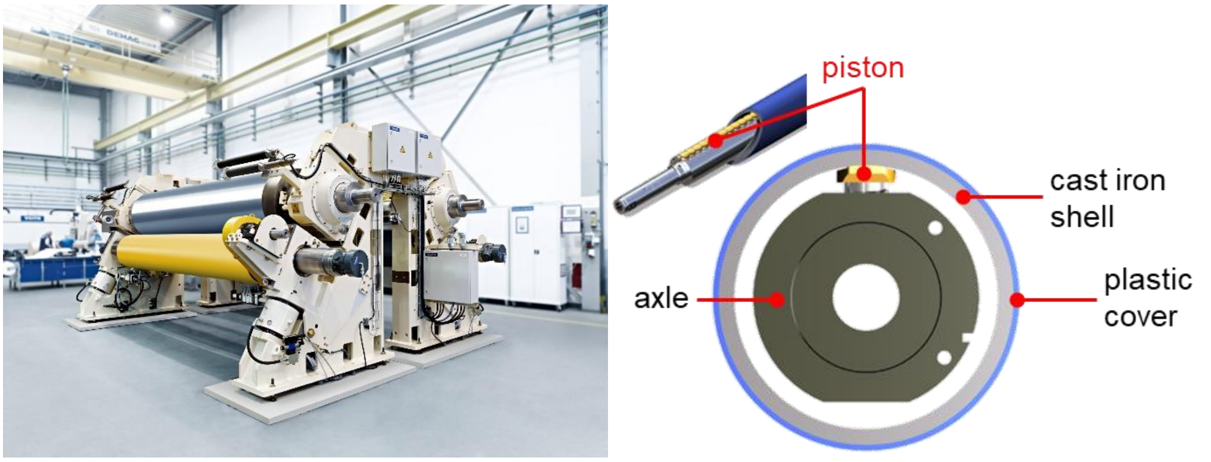

Figure 2: Exemplarily calender setup and the internal constructive roll structure [2].

Aim of this study is to generate a numerical model using a particle-based method to investigate the impact on the churning loss, in terms of torque, of a single piston domain. Churning losses occur because of the interaction between the rotating oil volume and the stationary piston.

2 NUMERICAL MODEL AND SETUP

The used numerical model takes the main components of a calender roll into account and consists of the following three parts, see **Figure 3**:

1. Cast iron shell and plastic cover which are combined to one solid, rotating body.
2. Piston (head and rod) and axle defined as two solid, stationary bodies.
3. Oil volume defined as fluid body.

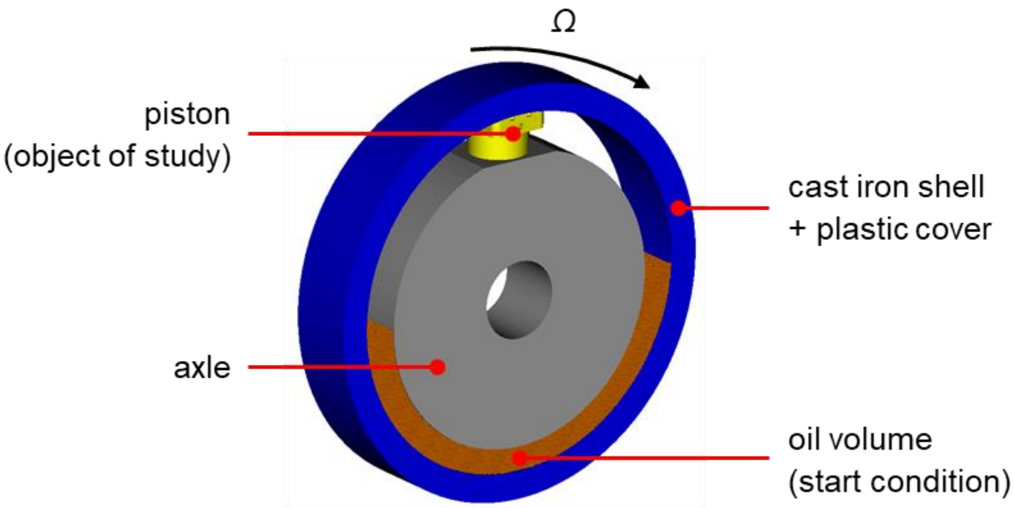

Figure 3: Numerical setup consisting of rotating cast iron shell and plastic cover, stationary axle and oil volume.

In total, four different volume cases are investigated to determine its impact on the churning loss, see **Figure 4**. After pre-processing, the oil volume is numerically discretized resulting in about 700,000 particles for the maximum oil volume case. The maximum occurring oil volume arises as a result of the minimum drain out of the device's oil chamber.

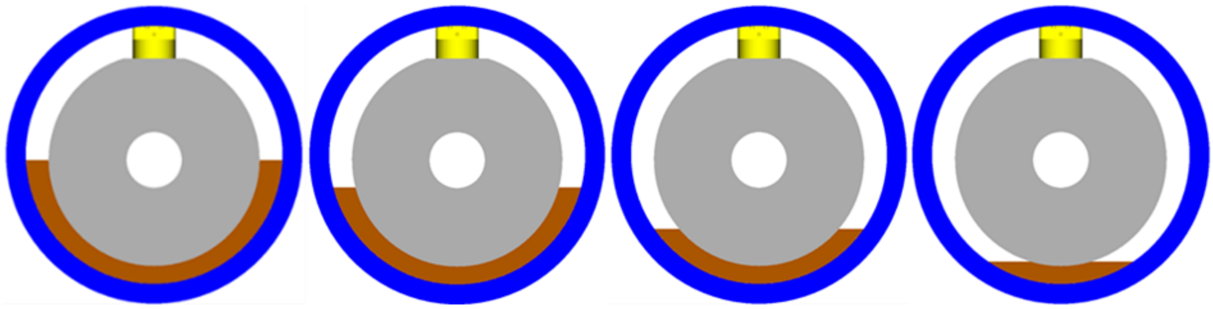

Figure 4: Variation of oil volume from left to right: 100%, 80%, 60% and 30%.

Each of the three other oil volumes (80%, 60%, 30%) is defined by the oil film thickness *h*, which typically occurs during operation. Hereby, it was assumed that a perfect oil ring is formed, see **Figure 5**.

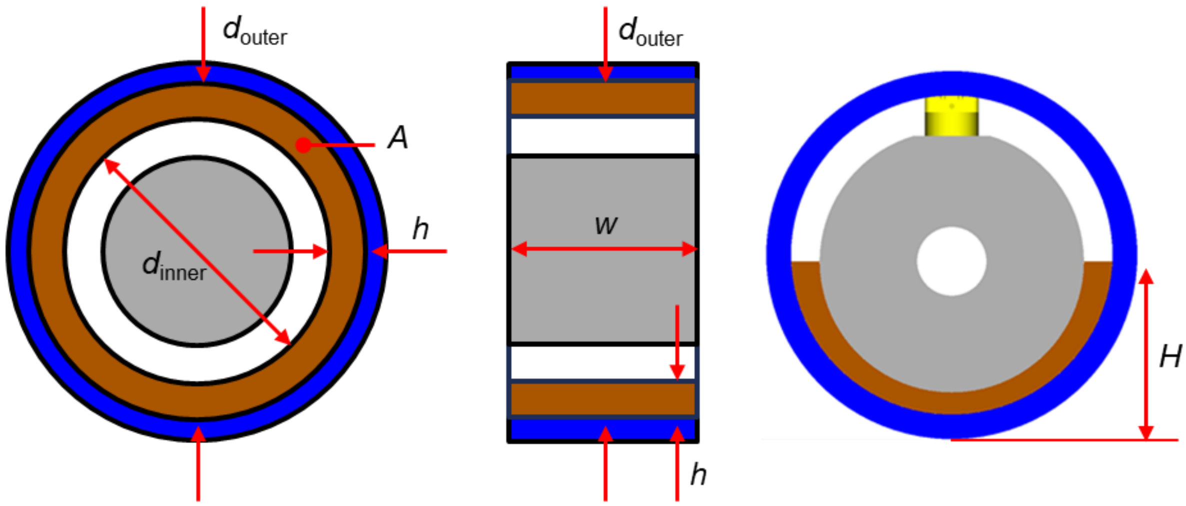

Figure 5: Parameters to define the formed oil ring and the related oil volume.

The film thickness of the rotating oil ring can be calculated using **Equation 1**.

$$h = \frac{d_{outer}}{2} - \sqrt{\frac{d_{outer}^2}{4} - \frac{A}{\pi}} \tag{1}$$

where d_{outer} stands for the outer diameter and *A* for the area of the ideal formed rotating oil ring.

The oil is defined according to ISO VG 100 [3] resulting in the fluid parameter which are listed in **Table 1**. It is assumed that the oil temperature is constant.

Table 1: Fluid parameters of used oil definition accoring to ISO VG 100 [3].

parameter	value	unit
density	900	kg/m³
thermal conductivity	0.20	W/(m K)
specific heat	2000	J/(kg K)
kinematic viscosity	3e-5	m²/s
surface tension coefficient	40	mNm

The commercial software Particleworks version 7.0.0 is utilized as a particle-based method to perform the numerical simulations, which uses the MPS approach [4]. Using the particle-based method, it was easier to realize the calender roll simulations and model all complex unsteady flow phenomena compared to "ordinary" CFD techniques, e.g. volume of fluid method (VOF). In direction of the machine axis translational periodic boundary conditions are applied. All walls are defined as adiabatic and smooth.

3 RESULTS AND DISCUSSION

This section is divided in three parts: Firstly, a general physical plausibility check is presented. Secondly, the results of the maximum volume flow are analyzed and discussed. Based on that, within the last part, the oil volume is reduced and the variants are compared.

3.1 Physical Plausibility Check

First, a simulation was performed without a piston to check, whether a stable rotating oil ring is formed or not. Hereto, **Figure 6** illustrates the simulation result of the last time step, which shows a physical plausible formation of an oil ring (see left). This result is quantitatively underlined by the determined torque, which converges to a steady solution (see right). In the following, the torque is used as a target value to quantify and analyze the churning loss.

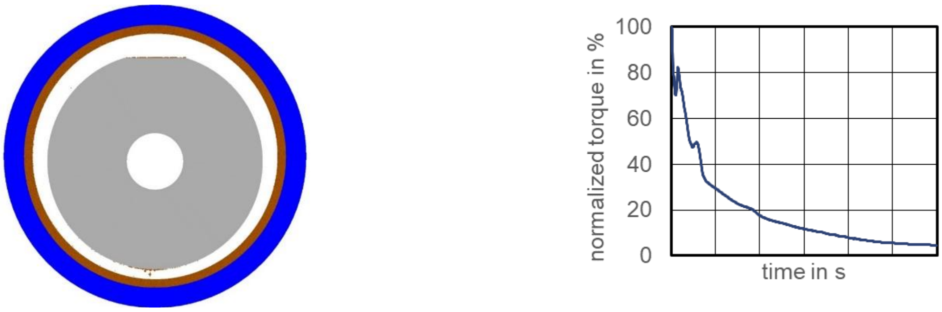

Figure 6: Torque change of configuration with 100% oil volume without piston for plausibility check.

3.2 Reference Case (100% Oil Volume)

Important time steps of the maximum oil volume case, labeled as reference case, are shown in **Figure 7**. Just after starting the particle simulation, the first oil particles hit the piston head and are bounced back according to Newton's third law. The piston head is a vertical plate with maximum drag. Consequently, the oil shows now a local countermovement compared to the direction of rotation. The following oil interacts with the upstreaming oil resulting in a flow deceleration and thus kinetic energy dissipation. Additionally, the oil volume which passes the piston, flows around the cylindrical rod. Here, a Kármán vortex street is formed, resulting in unsteady, oscillating flow conditions. This unsteady oil jet hits the rotating calender roll such that the flow is decelerated and highly turned.

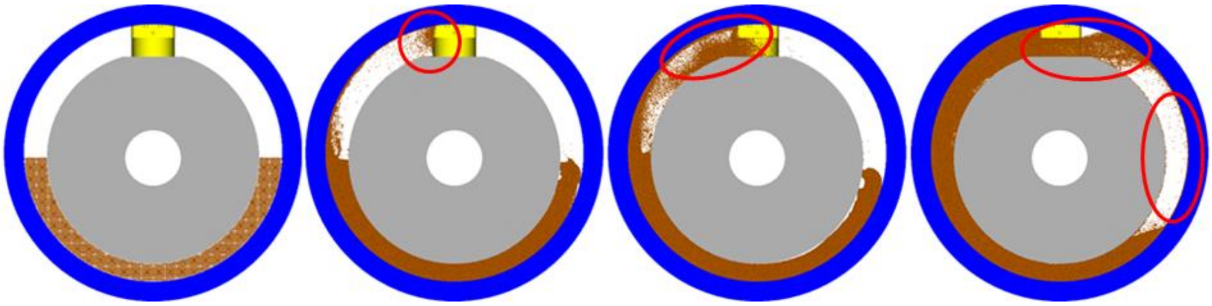

Figure 7: Rotating oil flow formation within calender roll with piston head (100% volume).

The particles of the numerical solution of the last time step shown in **Figure 7** are used as sample points to generate an interpolated oil surface. The interpolation result is visualized in **Figure 8**. Here, the impact of the partly reflected oil close to the piston head on the oil distribution can be seen. The oil in 10 o’clock position is very turbulent compared to the flow conditions within the fluid domain. The formation of the vortices constantly requires kinetic energy to keep the vortices alive. Moreover, the turbulent oil mixing leads to energy dissipation resulting in the oil heating up. That is why generally, oil has to be removed, cooled and injected again.

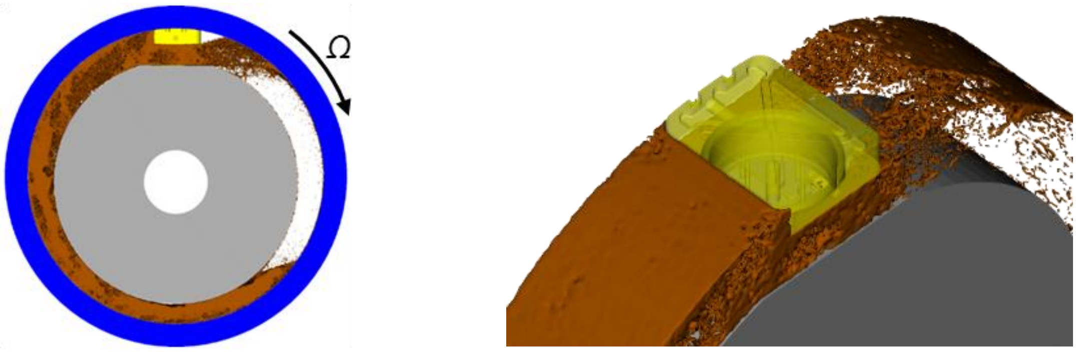

Figure 8: Interpolated surface to qualitatively analyze the oil turbulences.

The torque is determined to make a clear quantitative statement about the churning loss, see **Figure 9**. An oscillation of the torque can be seen which is caused by the physical phenomena described earlier. Since it is easier to compare integral values, first the moving average of the torque is determined. Based on this, the arithmetic mean is calculated hereafter. This value of the maximum oil volume is used as a reference value to normalize the torque for all cases in this paper. Therefore, the integral normalized torque is 100% for the 100% oil volume case.

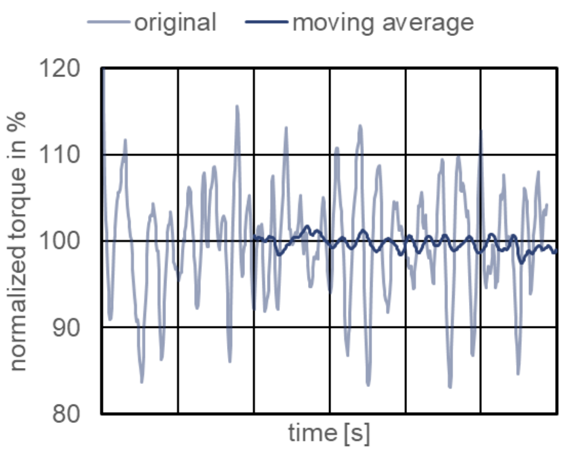

Figure 9: Determined time-dependent torque for maximum oil volume and its moving average (100% volume).

In reality, there is a continuous removal and injection of oil. Heated oil caused by friction is removed at 9 o'clock position, cooled and injected at 3 o'clock position, see **Figure 10**. Therefore, the oil is partly bypassed such that the amount of oil, which hits the piston at 12 o'clock position, is reduced. The numerical setup was modified to consider this. Hereto, an outlet was added for the removal and an inlet for the injection within Particleworks [5]. Both of them are coupled in such a way that the volume of oil which is removed is re-injected automatically.

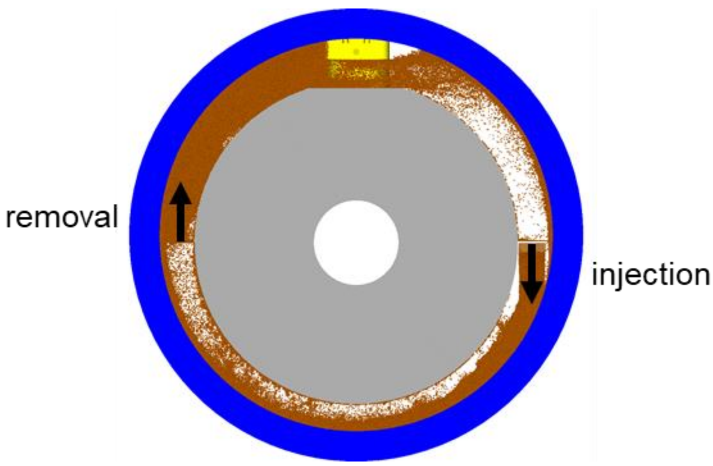

Figure 10: Rotating oil flow formation within calender roll with piston (100% volume).

The results without and with oil removal and injection are compared in **Figure 11**. As is can be seen, the oscillation is drastically reduced for the case whereby removal and injection is taken into account. This makes sense, since a smaller oil volume streams against the piston head and around the piston rod. However, the difference of averaged torque is only 0.8%-pts. so that the integral churning loss remains almost the same. Consequently, the oil removal and injection is neglected for the following oil reduction investigations.

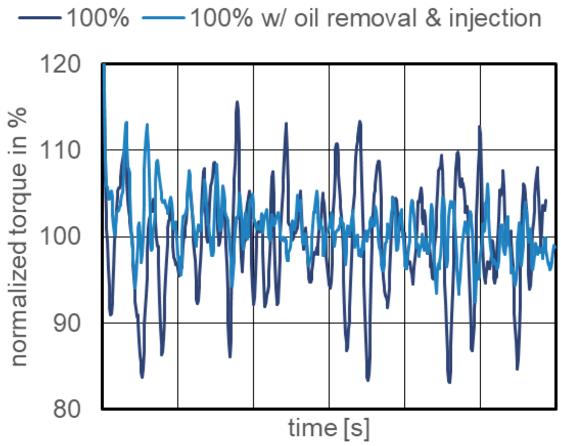

Figure 11: Torque curve taking oil removal and injection into account (100% volume).

3.3 Oil Volume Reduction

Within this section, the oil volume is reduced to 80%, 60% and 30% of the maximum oil volume. The numerical results of the torque are shown in **Figure 12**. It can be seen that the amount of oil within the calender roll has clearly an impact on the torque: smaller oil volumes result in lower torque. This is plausible, since a smaller amount of oil reduces for instance the drag, which occurs at the piston head. In addition, there is no linear relationship between the change of oil volume and resulting torque. This makes sense, since e.g. the drag force is proportional to the square flow velocity [6].

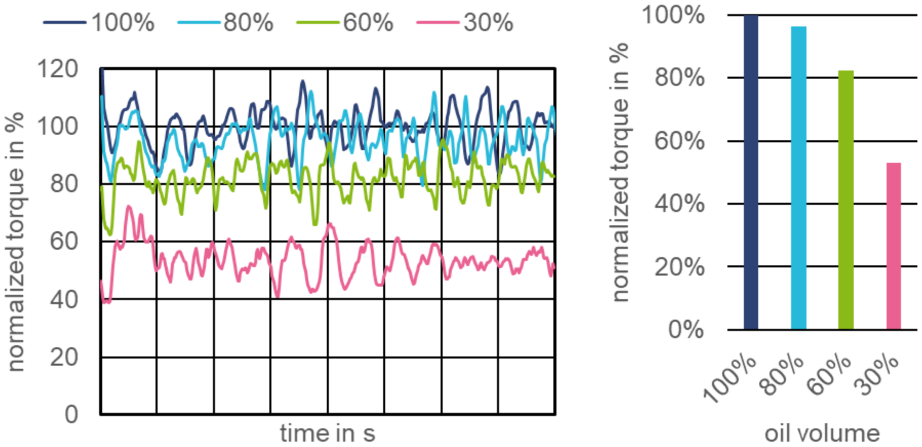

Figure 12: Change of torque dependent on reduced oil volumes.

4 CONCLUSIONS

- A periodic numerical model of a single piston within a calender roll was generated and successfully simulated using the commercial software Particleworks.
- Bypassing a specific amount of oil volume reduces the torque oscillation, but has no significant impact on the integral torque value respectively the churning loss.
- Reducing the oil volume leads to a decrease of the torque. The resulting integral torque reduction, and with that the churning loss, is highly non-linear.
- Understanding the main loss generation mechanisms within a calender roll is the key to design a calender which shows a minimum churning loss. This can be a significant source of cost savings for our customers. With this in mind, using a particle-based simulation method can indeed supports and accelerates the entire development process by taking full advantage in terms of virtual product testing.

5 ACKNOWLEDGEMENTS

The authors would like to thank Mr. Simon Harbeke from EnginSoft Germany for his software support within this project.

REFERENCES

[1] Blechschmidt, J. *Taschenbuch der Papiertechnik*. Carl Hanser Verlag, Ed. 2, (2013).
[2] J.M. Voith SE & Co. KG. *Internal Document*. (2021).
[3] International Standards Organization. *ISO 3448: Industrial Liquid Lubricants - ISO Viscosity Classification*. Ed. 2, (1992).
[4] Promtech Software Inc. *Particleworks: http://www.particleworks.com/home_en.html*. (2021).
[5] Promtech Software Inc. *Particleworks Theory Manual*. Software release 7.0.0, (2020).
[6] Schlichting, H. and Gersten, K. *Boundary-Layer Theory*. Springer-Verlag, Ed. 9, (2017).