Temperature distribution of a rubber compound in a channel flow around an oscillatory rotating disk

polymer technology

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Many of the transport methods used nowadays drive on the road with the help of tires. For tire manufacturing, a high throughput is desired but is limited by the viscous heating. A system containing a single-screw extruder combined with an external gear-pump (Figure 1) is typically used for processing tire compounds. The heat and fluid flow are numerically studied using the finite element method with a focus on the external gear-pump.

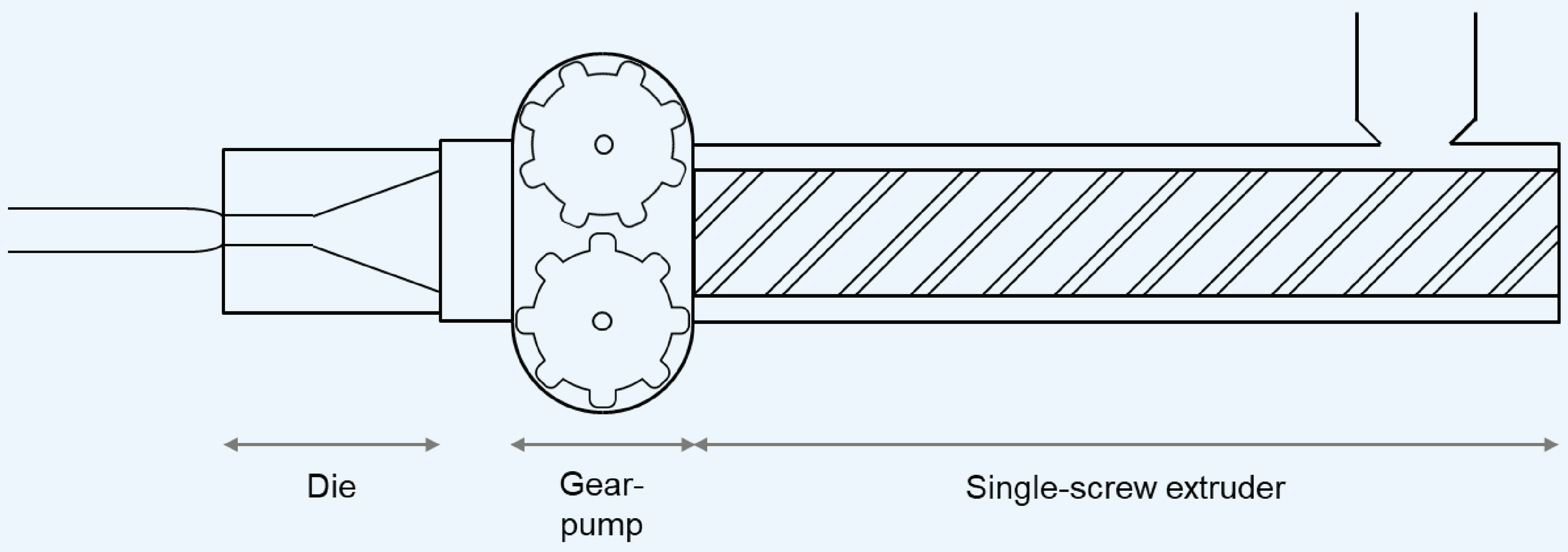

Figure 1: Schematic representation extruder/gear-pump system.

Rubber compounds

Tire compounds consist of many ingredients. These compounds are non-Newtonian shear-thinning materials, i.e. the viscosity decreases at higher deformation rates. For the power-law like rate dependency of the viscosity the Carreau model can be used (Figure 2a). Rubber compounds also exhibit a strong dependence on temperature (Figure 2b). This can be captured with the Williams-Landel-Ferry (WLF) equation. First, we focus on the heat flow and thus use a constant viscosity for the flow simulations.

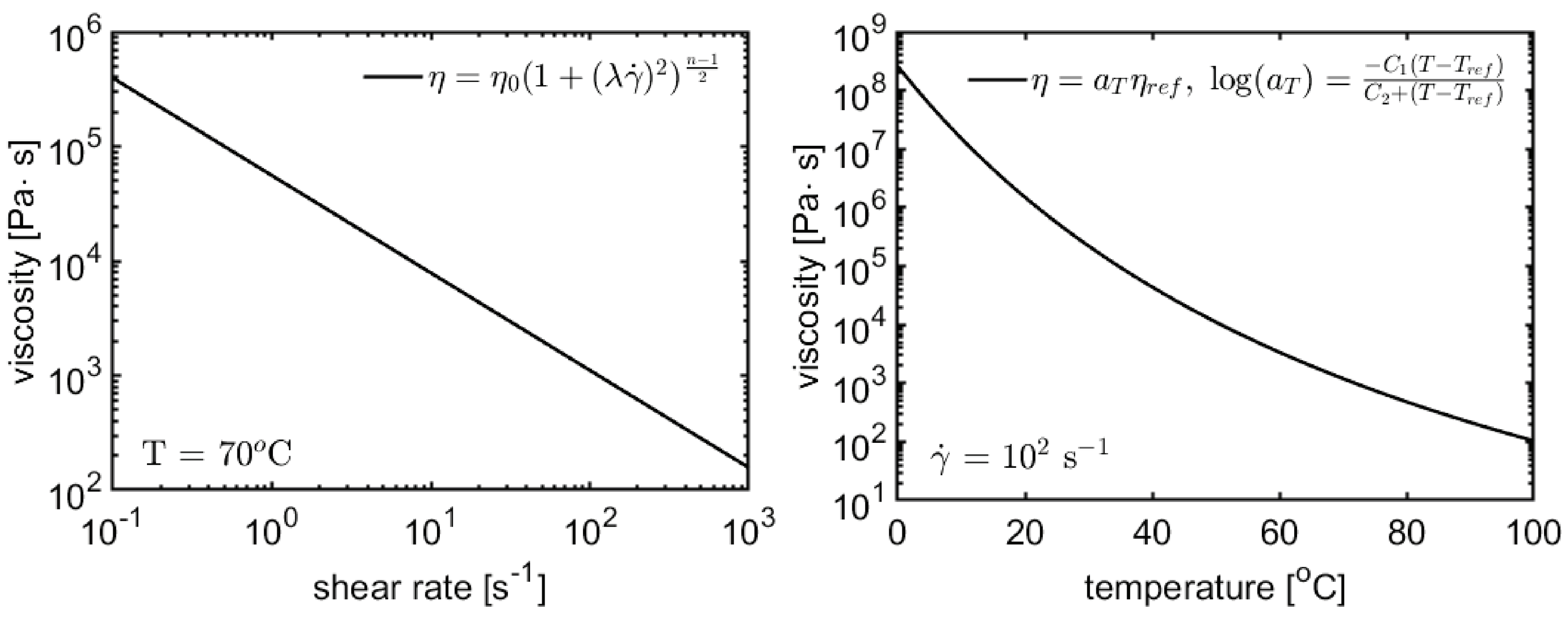

Figure 2: The viscosity of a typical rubber compound: (a) power law like shear-thinning behavior, (b) temperature dependency of the viscosity.

Rotating disk in channel flow

The external gear-pump is a fairly difficult problem containing a complex geometry and high local shear rates. The geometry is simplified to an oscillatory rotating disk in a channel flow. By this means, the locally high shear rates in combination with the material behavior of a rubber compound are studied first. These shear rates give rise to local heating of the fluid (Figure 3).

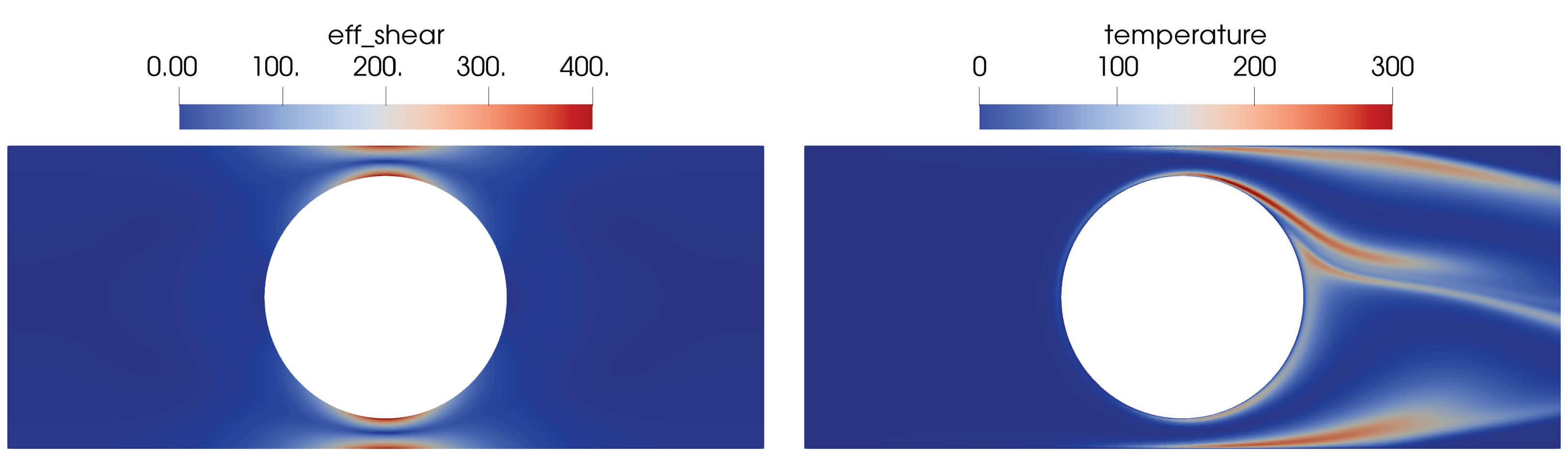

Figure 3: The oscillatory rotating disk ($\|\omega\|$=5 rad/s, f=1 Hz) in a channel flow (Q= 500 mm^2/s) after one second: (a) effective shear rate, and (b) temperature.

Figure 3 shows that thin high temperature layers, caused by locally high shear rates, are dragged along with the fluctuating flow. Choosing the right mesh size to capture these local temperature changes is of great importance.

Mesh convergence

To obtain a trustworthy outcome of the simulations, convergence of the mesh needs to be assured. The material properties of the compounds result in a fast development of the velocity field and an extremely slow development of the temperature field. This leads to thin high temperature layers. For convergence of this temperature field, the error is defined as

$$\text{error }(\text{x},\text{y}) = \frac{|T(x,y) - T_{\text{ref}}(x,y)|}{\max(T_{\text{ref}})},$$

where T_{ref} is the temperature field obtained using the element size h=$H/320$. The parameter H is the height of the channel. Figure 4 shows that the error decreases with decreasing element size. For an element size of h=$H/80$ the maximum error is decreased to 1,5%, which is close to a typical convergence criterion of 1%.

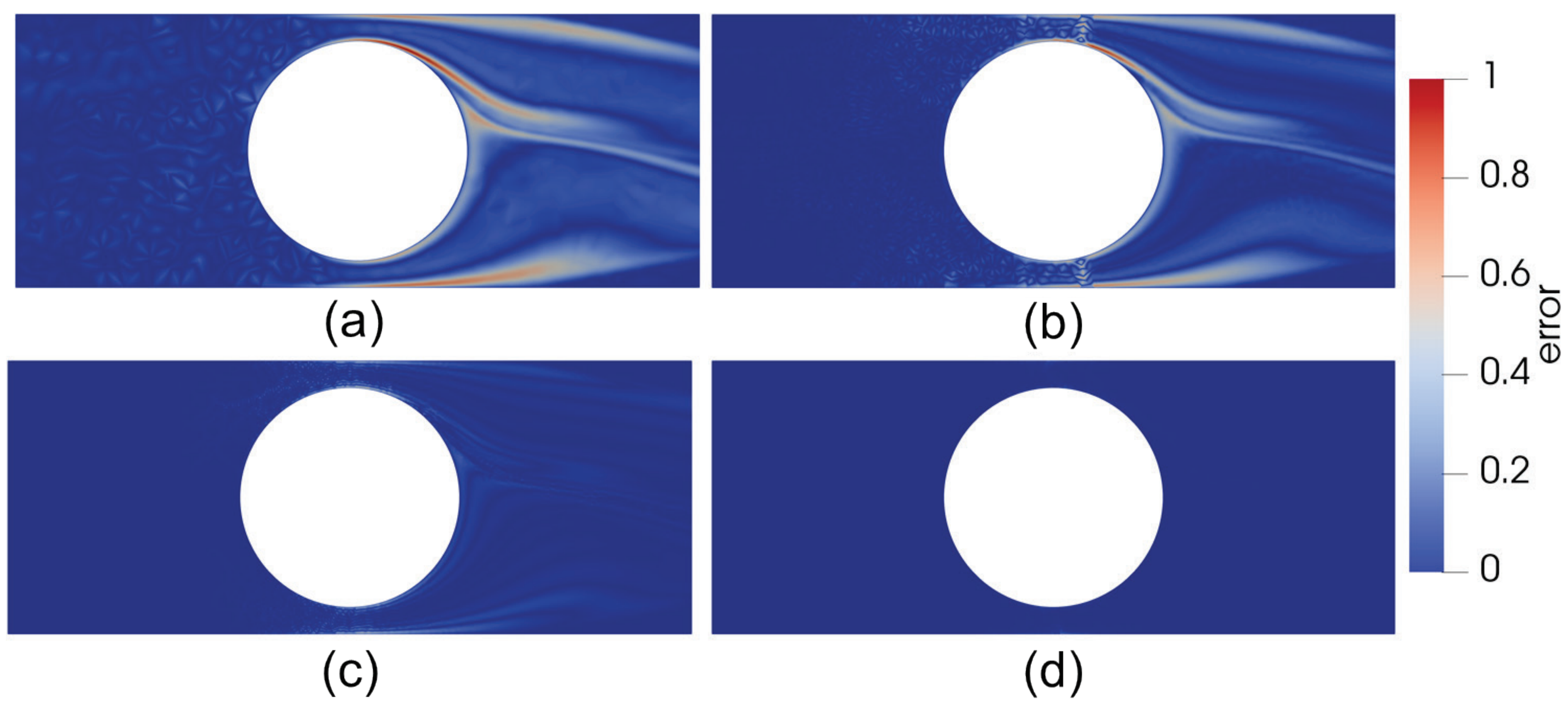

Figure 4: Error of temperature field compared to element size h=$H/320$: (a) h=$H/10$, (b) h=$H/20$, (c) h=$H/40$ and (d) h=$H/80$.

Crosslinking

For rubber compounds, high temperatures result in crosslinking behavior. Crosslinking leads to a drastic increase in viscosity, and should therefore be prevented. Implementation of the crosslinking behavior of rubber compounds with the help of an evolution equation for the state of cure (ranging from zero to one) is the next step.

Conclusions

A simplified problem, the oscillatory rotating disk in a channel flow, is used to study the combination of the locally high shear rates and the material behavior of rubber compounds. These shear rates result in local heating of the rubber material, which creates thin high temperature layers in the flow. Convergence of the temperature is assured using an element size of h=$H/80$.