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Finite element modelling of the fluid temperature in a plate–plate rotational rheometer in oscillatory tests

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ABSTRACT

Rigorous temperature control of rheological measurements is of great importance since even temperature distribution in the sample is required for an accurate measurement. This article explores the use of finite element methods (FEM) for experimental design and quality assurance. The chosen geometry consists of a plate-plate rotational rheometer (Physica UDS200 rheometer). The fluid sample was Polybuthene-1. FEM analysis has been shown to be a useful tool.

INTRODUCTION

Correct temperature settings are of paramount importance during rheological measurements since the viscosity and other rheological parameters strongly depend on temperature.

Analysis of temperature profiles with finite element methods has previously been performed on plate/plate and cone/plate rheometers, [1, 2].

This paper focuses on the use of a simple and friendly user finite element software[a] (FEM) to investigate its performance for quality assurance and experimental design in transient rheological tests in a plate-plate rheometer. The calculations made are compared with experimental measurements[3].

The gap between the two plates was varied from 0.5 mm to 1.2 mm, and the measurements were performed in oscillation, so the fluid sample between the plates was almost stationary.

The calculations were made on a Jacobian mesh (4 points) of the Peltier plate, the fluid sample and the MP31 plate. The temperature at the bottom of the Peltier plate was assumed known and accurately controlled. The heat flow to the surroundings was calculated by convection with an adjusted heat transfer coefficient.

The use of a FEM friendly user software can be a great help to improve experimental design in rheometers, as well as it can increase measurement accuracies when required by scientists which are not working daily with FEM calculations.

THE FEM PROGRAM

The calculations were performed with the computer program CosmosWorks that is an integrated part of SolidWorks[b].

The parts were first drawn to scale and assembled in SolidWorks. The fluid volume between the plates was drawn as an individual part. All the parts were then meshed in CosmosWorks.

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[a] CosmosWorks, SolidWorks Corp., Boston, MA.

[b] SolidWorks Corp., Boston, MA.

Calculation procedure

The calculations were defined as transient heat transfer problems with appropriate initial values and boundary conditions.

First a steady state simulation was run with the Peltier temperature set to 40 °C and the heat transfer coefficient between the MP31 and the surrounding air was varied iteratively to find a suitable value matching the observed and calculated shaft temperature. This steady state solution was also taken as the initial condition to the other set of transient calculations where ramp or step variations to the Peltier temperature were specified.

The Peltier temperature versus time could in CosmosWorks be specified as a temperature versus time curve as shown in Fig. 1.

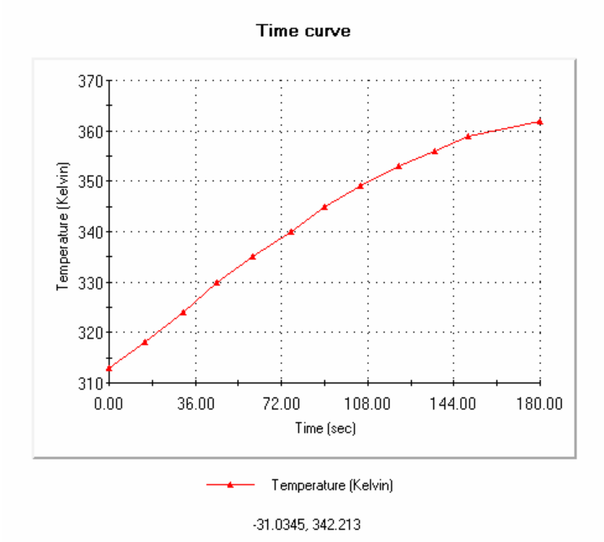

Figure 1: Peltier temperature boundary condition specified in CosmosWorks.

MODELLING

The Peltier plate was modelled as a cylindrical element with a diameter of 81 mm and a height of 10 mm. The bottom surface was temperature controlled. The fluid element was modelled as a cylindrical element with 50 mm diameter, and the height equal to the gap spacing (either 0.5 mm or 1.2 mm).

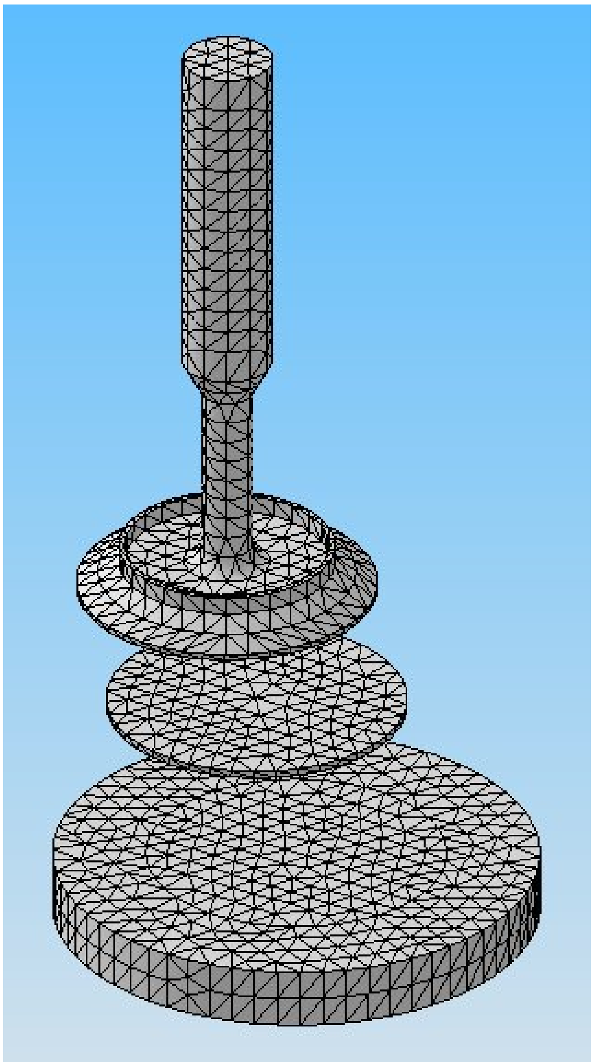

Figure 2: Basic mesh of MP31, fluid element and Peltier plate in an exploded view with a coarse mesh.

The MP31 top plate was exactly drawn to scale in SolidWorks with a 50 mm maximum diameter. The basic geometries are shown in Fig. 2.

Initial steady state calculations were first performed to give the initial temperature distribution in the geometry with the Peltier temperature set at 40 °C and with a surrounding temperature of 23 °C. It was found that the observed steady state temperatures were achieved using an external heat transfer coefficient of 11 W/m^{2}K between the surfaces and the surrounding air.

The following properties were assigned: Peltier plate (Aluminium): ρ = 2700 kg/m^3, k = 200 W/mK, c_p = 900 J/kgK. Polubuthene-1: ρ = 866 kg/m^3, k = 0.22 W/mK, c_p = 1939 J/kgK. MP31 (Steel): ρ = 8000 kg/m^3, k = 16.3 W/mK, c_p = 500 J/kgK.

The density of Polybuthene-1 was determined by measuring the mass of a known volume. The specific heat was determined using a differential scanning calorimeter (DSC), (micro DSC III, Setaram Instrumentation, Caluire, France). The thermal conductivity value of 0.22 W/mK was taken from the literature. We tried to measure the thermal conductivity by the thermal comparative method of Powell[4]. Teflon was used as the insulating material, Teflon has a similar value of thermal conductivity to a reported value[5] of Polybuthene-1, (poly(but-1-ene) and this induced a significant error in the measurement. It was concluded that the reported value was of the right order of magnitude.

The steady state calculations were performed on a mesh consisting of 9093 elements with 14673 nodes and 13306 degrees of freedom. The calculations were performed on a relatively standard PC (Dell Precision 670 Workstation with a Xeon processor and 2 GB RAM). The maximum computing time was of the order of a few minutes for each transient case.

The steady state initial condition was used as the starting point for the transient calculations, where the bottom surface of the Peltier plate was specified to vary according to a specified temperature versus time curve.

RESULTS AND COMPARISONS

It was straight forward to make the detailed 3D drawings of the hardware in SolidWorks. The program has a very intuitive user interface. The drawings made of each component were then assembled, and properties were assigned to each part of the assembly. The geometry was then ready for the finite element analysis.

The transient temperature calculations were performed with the integrated software package CosmosWorks. The following input was required: Material properties, i.e. density, specific heat and thermal conductivity. The heat transfer coefficients with the surroundings had to be specified and the initial conditions had to be specified or they could be taken as the end result of a previous calculation. The results obtained here were taken using this latter type of initial condition type input.

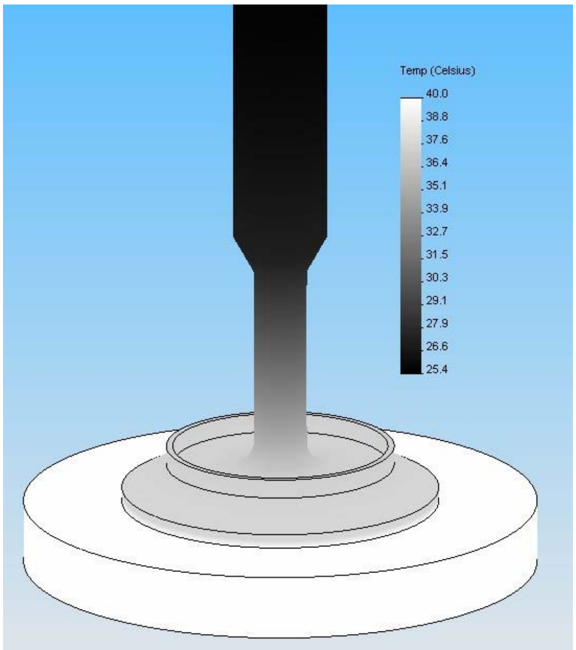

Figure 3: Steady state temperature distribution at 40 °C Peltier temperature.

The first calculation was a steady state calculation with the Peltier plate set to 40 ºC. Several calculations were made with different values of the external heat transfer coefficient. It was found that a value of 11 W/m^{2}K gave a good match between calculated and observed temperature distribution. The resulting temperature distribution is shown in Fig. 3.

The steady state temperature distribution was used as the initial condition for the transient calculations.

The transient calculations aimed at simulating a sudden step change in Peltier temperature set point from 40 ºC to 90 ºC. Experimental data for such a step change has been published[3] and was therefore a good testing case, shown in Fig. 4. It was seen that the fluid temperature ends up at approximately 85 ºC and that the surface of the conic plate (the MP31) at approximately 82 ºC.

The Peltier plate temperature versus time boundary condition was taken from the experimental results, and the transient calculations were made with an external heat transfer coefficient of 11 W/m^{2}K, the same value as was used in the steady state case.

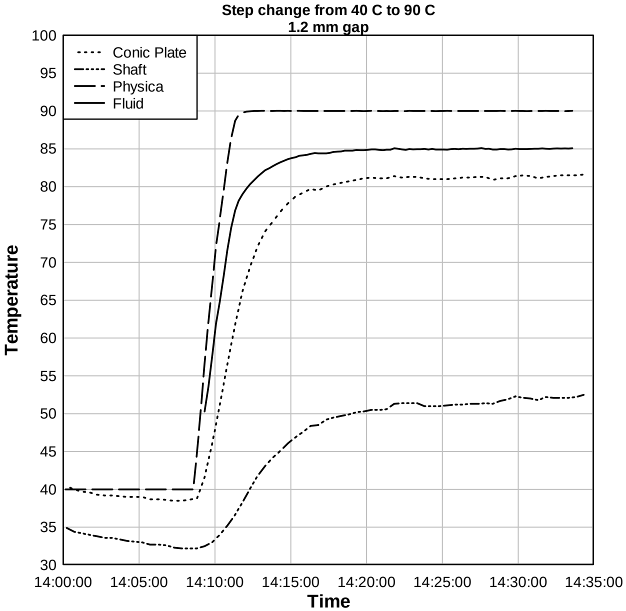

Figure 4: Experimental results[3] showing the temperature transients related to a step change in Peltier plate set-point temperature from 40 ºC to 90 ºC.

The temperature at different locations on the MP31 top plate, Fig. 5, were chosen and plotted versus time, Fig. 6.

We observe that the temperatures of the MP31 levels off at approximately 82 ºC.

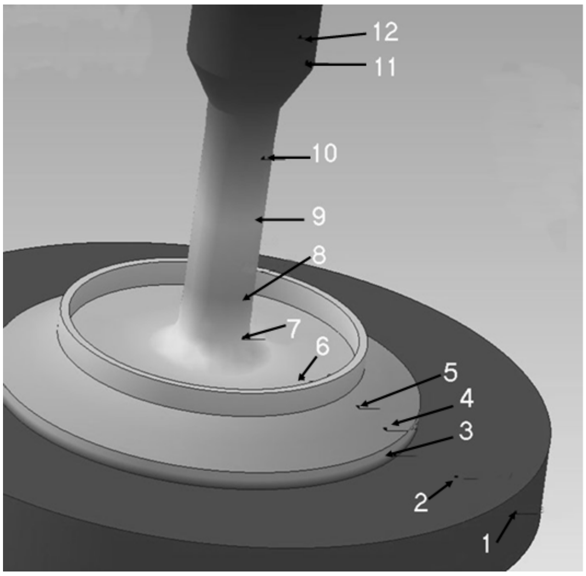

Figure 5: Positions of temperatures shown in Fig. 6.

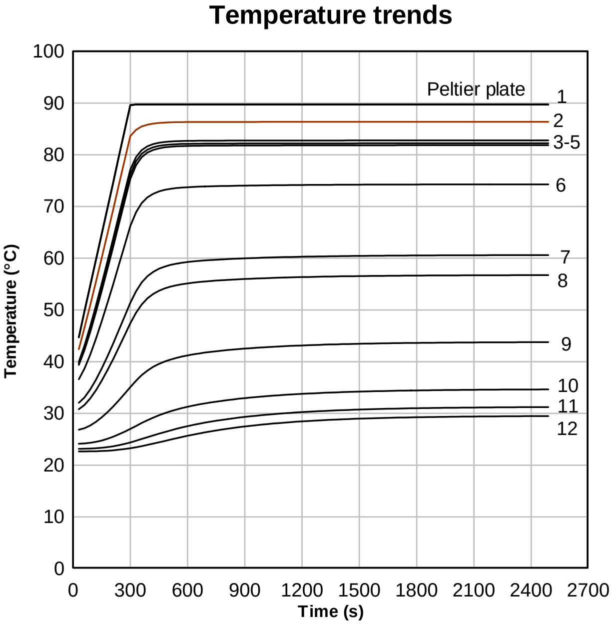

Figure 6: Calculated temperature versus time for step input in Peltier plate temperature from 40 °C to 90 °C. Curve number indicates positions according to Fig. 5.

DISCUSSION

Calculation of the steady state situation at 40 °C was matched when an external heat transfer coefficient of 11 W/m^2K was employed, and this value is of the right magnitude[6].

The plots of temperature versus time at different locations in the assembly show that the steady state temperature of the lower part of the MP31 levels off at approximately 82 ºC, which matches well with the experimental results[3].

The employment of FEM methods to quantify effects of transient temperature in fluid samples undergoing rheological testing seems appropriate. The analysis is relatively fast when one is acquainted with the software. A same geometry can be re-used for future cases. The SolidWorks – CosmosWorks programs have a very user friendly interface.

It is important to ensure complete control of experimental testing conditions during rheological measurements. In some cases it is not obvious that the temperature control is good enough, and for complex transient testing conditions it seems like FEM method can be used as means for experimental quality assurance and for experimental design. FEM methods can improve the measurements of fluids with viscosities highly affected by temperature and fluids having low heat transfer coefficients.

CONCLUSIONS

The conclusions from this study can be summarized as follows:

- The specification of initial condition and transient boundary conditions were readily done in CosmosWorks by employing temperature versus time diagrams/tables, and had a good match with the experimental data.
- The calculations with FEM were relatively quick on the normal type of PC employed in this work.
- FEM analysis can be used to evaluate the conditions that the fluid sample experiences during transient rheological testing.
- FEM analysis can be used as a means for experimental quality assurance and to improve experimental design, specially in fluids having high temperature dependent viscosities and for fluids having low heat transfer coefficients.

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