ing an insulated chamber. Using solid carbon dioxide, cold ambient temperatures was obtained (table 3 gives an estimate of about -20 C°). A heat source was used for creating the high ambient temperature environment. Figure 3 shows how a well insulated heat chamber can be constructed. Pictures of the set-up are shown in figure 4.

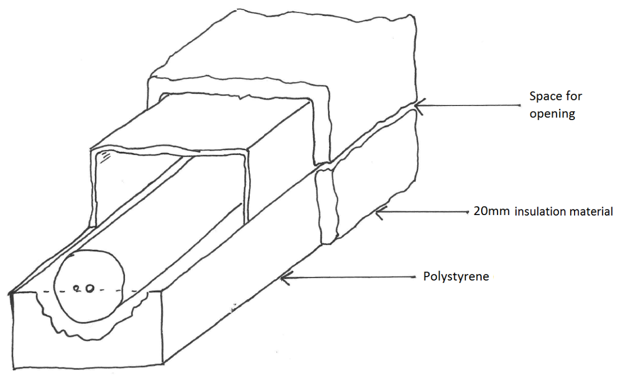

Figure 3: Sketch of how to insulate an accumulator from the environment

In order to stress the numerical models, steep pressure gradients are experimentally obtained. Practical experience has shown that it is easier to predict the behaviour at small pressure and temperature gradients than the opposite. To obtain high gradients, the gas was compressed and expanded by a realistic in application rate. An example of the expansion and compression time series is given by figure 5.

In the following, the measured temperatures and pressures are plotted versus simulation results with the experimentally obtained volumes as input. In this way, it is easy to see which real gas model best fits experimental results.

4 Results

A limited portion of the generated results are presented. However, results from both low, medium and high ambient temperatures are shown. Also, both temperature and pressure measurements are compared to calculated results. Please note that a first order filter was used on the temperature data to limit noise. Of course this results in phase transition which should be ignored.

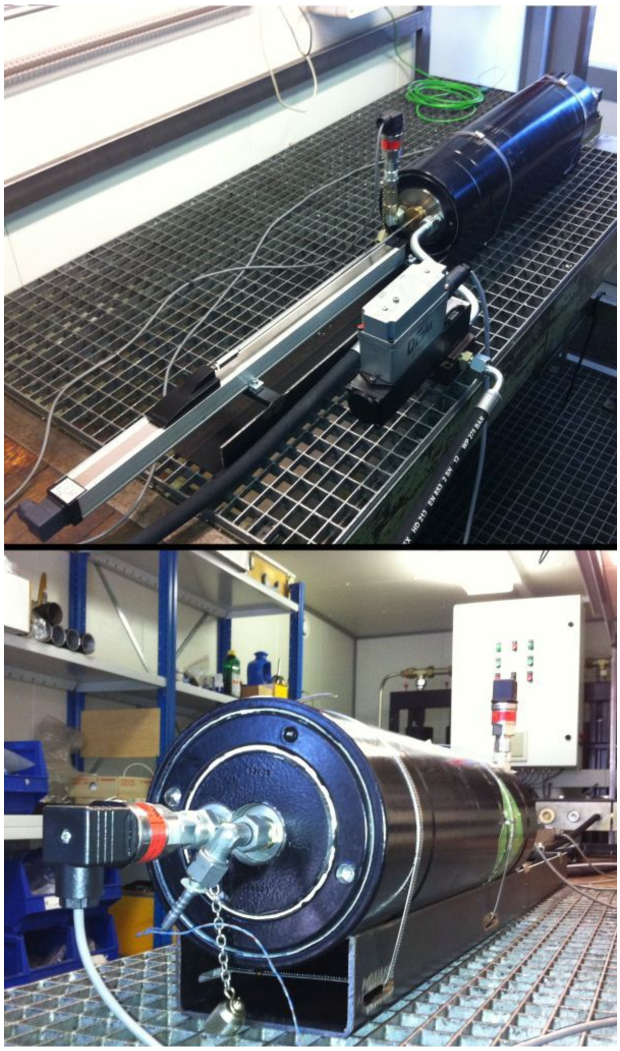

Figure 4: The setup from two angles.

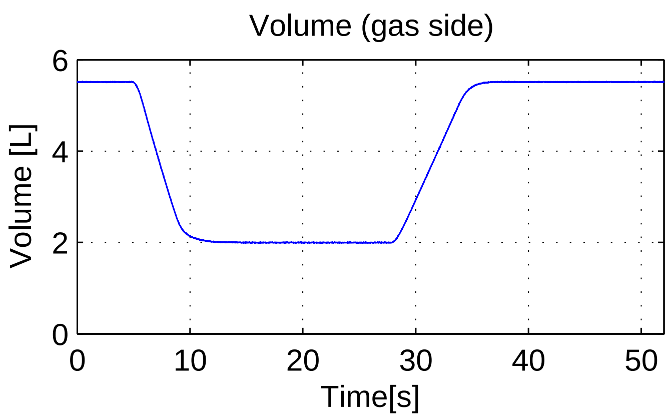

Figure 5: An overview of the experimental compression and expansion of the accumulator gas.

By driving the real gas model with the measured temperature, that is, using the data from the right hand side plots to drive the calculations in the left hand side plots, plots like figure 12 can be created.

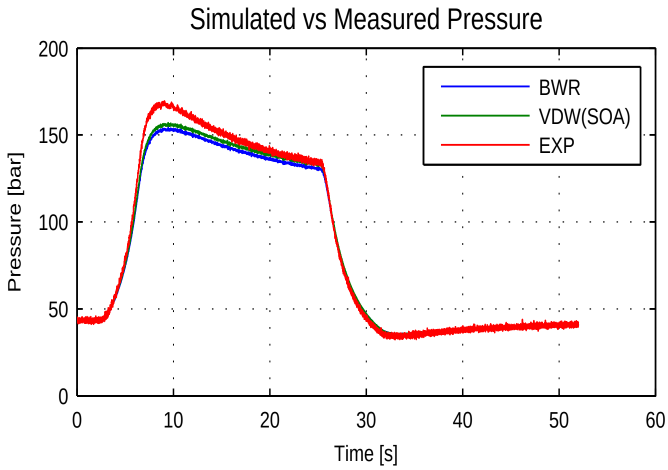

Figure 6: $p_0 = 48$ *bar,* $T_0 = 30°C$

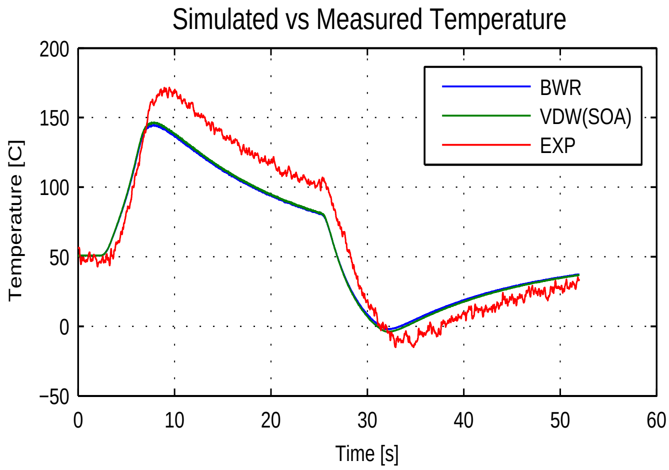

Figure 9: $p_0 = 48$ *bar,* $T_0 = 30°C$

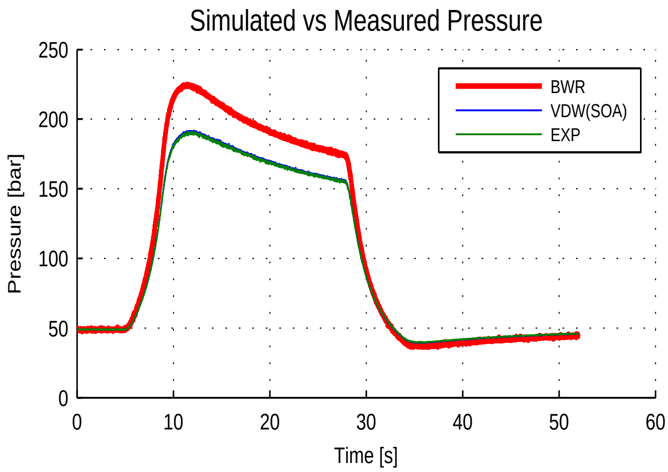

Figure 7: $p_0 = 48$ *bar,* $T_0 = -5°C$

Figure 10: $p_0 = 48$ *bar,* $T_0 = -5°C$

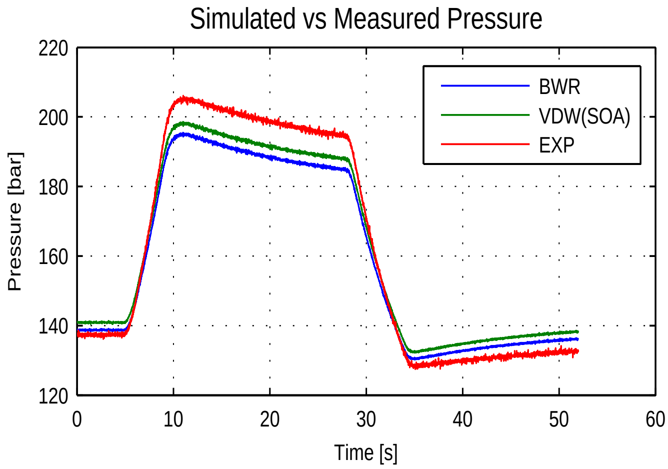

Figure 8: $p_0 = 140$ *bar,* $T_0 = 80°C$

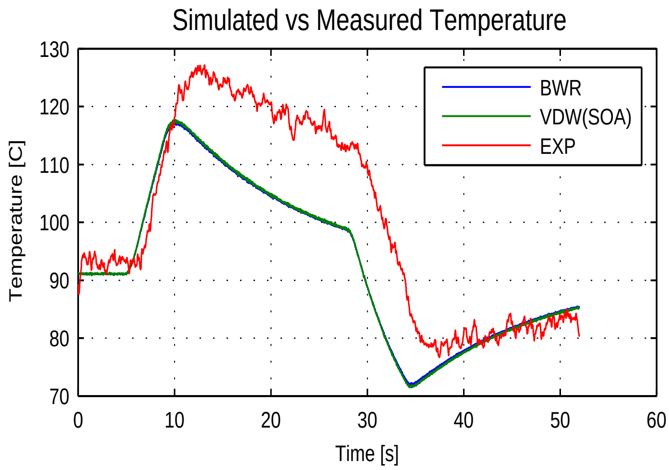

Figure 11: $p_0 = 140$ *bar,* $T_0 = 80°C$

5 Discussion

There are two clear observations from the presented results: Firstly, the two real gas models resemble in comparison to

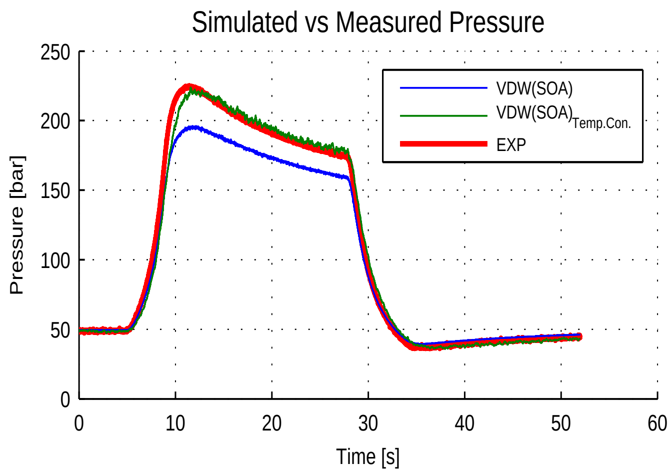

Figure 12: $p_0 = 48$ bar, $T_0 = -5°C$, pressure calculations with calculated versus measured temperature input.

the experimental results. They both predict pressures that are some 5-10 bar lower than measured. At higher compression and expansion ratios, the calculation error is higher. Secondly, there are some clear deviations between the simulated data and the measured data. The first observation enlightens the benefits of the Soave-Redlich-Kwong equation. While maintaining the overall accuracy, it greatly reduces computation times.
The second observation requires some examination. Clearly, some error sources have to identified. Several such error sources could be suggested:

- Bad measurements
- Inaccurate real gas model
- Incorrect or inaccurate unsteady model

In the following, each of these suggestions are examined.
Great effort has been put into validating and calibrating the temperature measurement devices in controlled environments prior to the research investigations. If the temperature measurements were bad despite the validation attempts, bad pressure calculations would be a result. However, as seen in figure 12, the pressure calculations are much more accurate if the real gas model is evaluated using the measured temperature.

Figure 12 is data from the same experimental run as figure 7. It can be seen that much more accurate pressure calculations can be performed if the measured temperature is used as input to the real gas model. Similar results are obtained for all other parameters, though not presented here. This serves to validate:

- The real gas model
- The pressure measurements
- The temperature measurements

It can therefore be concluded that the primary source of error is the limited accuracy in the thermodynamical model, equation 8. By analysing the presented data, this work serves to suggest the need for a better thermodynamical model, in order to precisely determine the dynamical behaviour of accumulators. The presented thermodynamical model has limited accuracy, because it does not model the accumulator wall. It merely suggests that the heat is transferred from the accumulator gas to the surroundings. Instead, a more precise model would employ a thick wall solution for the accumulator wall. Also, the heat conduction from the hydraulic oil to the accumulator gas (and vice versa) is not modelled. Especially when the ambient temperature are very different from the oil temperature, this will have a significant contribution.
Aside from these major issues, minor error sources in the thermodynamical model can be identified. One minor error source is the absence of the heat generated by the viscous oil in the model and also of gas flow at the accumulator wall. Especially the viscous gas flow heat contribution is a challenge to model as a function of volume change. It is likely to have negligible effect at low rate of volume change, since flow phenomena are unimportant to the problem compared to compressibility effects.
The model may be constructed by employing a heat transfer model for the accumulator wall. The model should include heat convection from the gas to the wall, heat conduction through the wall (such that temperature in the wall changes with the wall depth), heat conduction from the wall to the surroundings and also radiation from the accumulator to adjacent surfaces. Also, the model should include heat contribution from the accumulator oil by conduction though the piston to the gas. This should all serve to enlarge the insulation properties of the accumulator with respect to the gas, thus increase the peak temperature after compression.
As can be seen in the results, the presented model predicts temperature- and pressure changes better after the expansion than after the compression. As accumulators are loaded during wind turbine operation at much slower rates than conducted in this experiment, the need for performance predictions here vanishes. As the accumulators empty very rapidly during emergency stops of the turbines, the crucial performance phase of the accumulator is during gas expansion. The need for a better thermodynamical model, as discussed above, may therefore have greater importance for areas in hydraulics where accumulators are loaded at high rates of volume change.

6 Conclusion

The presented thermodynamical model has limitations at high rates of volume changes. This is most likely due to the inaccurate modelling of the insulation properties of the accumulator. The inaccuracies are some 5-10 bar difference between measured and calculated data just after compression and expansion. The difference is higher for higher compression/expansion ratios and the difference approaches zero for infinitely slow rates of volume changes.

A better thermodynamical model can maybe be established by implementing a heat balance on the accumulator wall in the model.
The two presented real gas models; The Benedict-Webb-Rubin equation and the Soave-Redlich-Kwong equation are almost similarly accurate. The Soave-Redlich-Kwong model suggests a slightly higher pressure after compression compared to the Benedict-Webb-Rubin equation. Since the Soave-Redlich-Kwong equation is much more efficient than the Benedict -Webb-Rubin equation, this work concludes that the Soave-Redlich-Kwong equation should replace the Benedict-Webb-Rubin equation in future simulations.
The quality of the measurements were confirmed by calculating the pressure using the Soave-Redlich-Kwong equation with the measured temperature, and then comparing the calculations to measured pressures. Since the calculated data matched the measured data extremely well, it is concluded that the measurements are accurate, dynamic and reliable. Also, it is concluded on this basis that the Soave-Redlich-Kwong real gas model is accurate enough for any application within the wind turbine technology.

References

[1] Pourmovahed A. Otis, D. R. An Algorithm for Computing Nonflow Gas Processes in Gas Springs and Hydropneumatic Accumulators. *Journal of Dynamic Systems, Measurement, and Control*, 107:93–96, 1985.

[2] A Pourmovahed and D. R. Otis. An Experimental Thermal Time-Constant Correlation for Hydraulic Accumulators. *Journal of Dynamic Systems, Measurement and Control*, 112:116–121, 1990.

[3] S. Rotthäuser. *Verfahren zur Berechnung und Untersuchung hydropneumatischer Speicher*. Fakultät für Maschinenwesen der Rheinisch-Westfälischen Technischen Hochschule Aachen, Essen, Germany, 1993.

[4] D. R. Otis. New Delvopment in Predicting and Modifying Performance of Hydraulic Accumulators. *National Conference on Fluid Power*, 1974.

[5] G. Soave. Equilibrium Constants from a Modified RedlichKwong Equation of State. *Chem. Eng. Sci.*, 27:1197–1203, 1972.