DRAFT VERSION

Preliminary results

- Estimation of effective porosity in coal seams using parameter matching -

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GLOSSARY

Please pay attention to the glossary for a better understanding of the report content.

- Steady-state experiment - in this work it is assumed that such an experiment represents the sequence of steady-state regimes at every measured time step.
- Unsteady experiment - in this work the transient flow is achieved by the rapid closure of a mass flow controller leading to a fast uncontrolled pore pressure drop in the core sample.
- Steady-state permeability - coal permeability obtained from the steady-state experiment.
- Unsteady-state porosity - coal porosity obtained from the unsteady-state experiment.

The density of injected gas (helium) can be estimated using the approximation provided by [1]. Helium viscosity at experimental conditions is depicted using the approximation obtained by [2]. Please refer to Fig. 1 for more details.

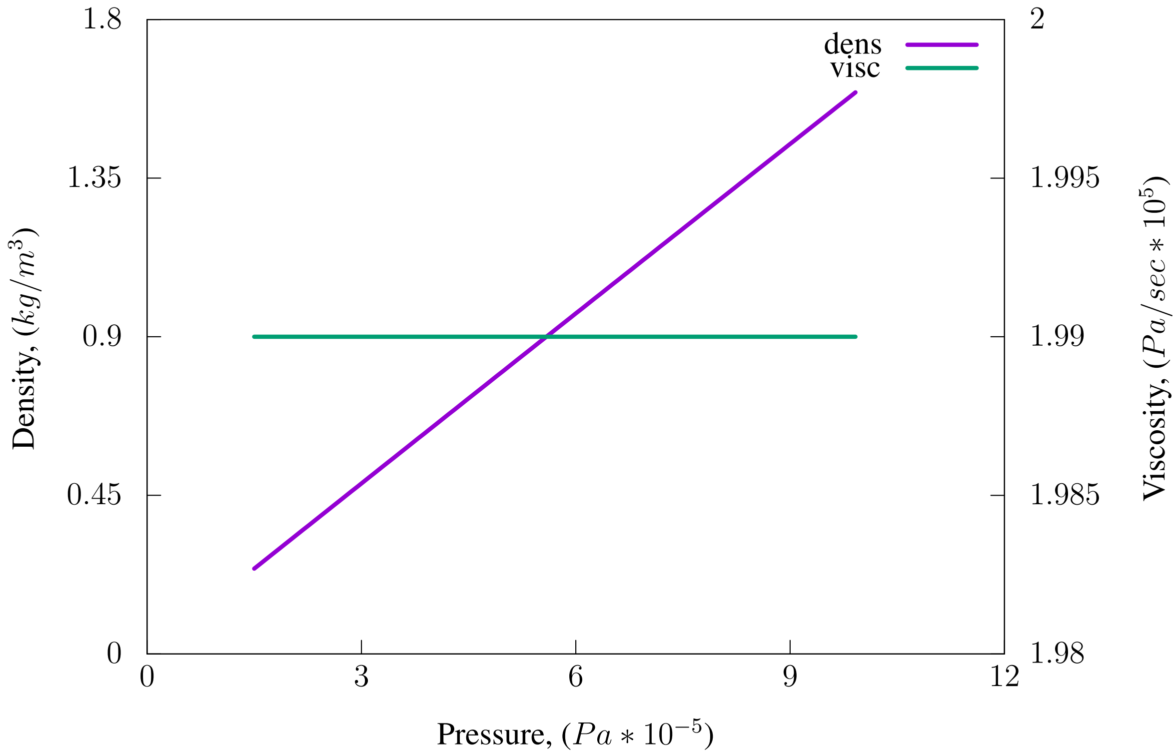

Figure 1: Helium density and viscosity approximations.

The density of methane at experimetnal conditions can be estimated using the Peng - Robinson equation of state [3]. Methane viscosity is obtained using the approxiamtion from [2]. Please refer to Fig. 2 for more details.

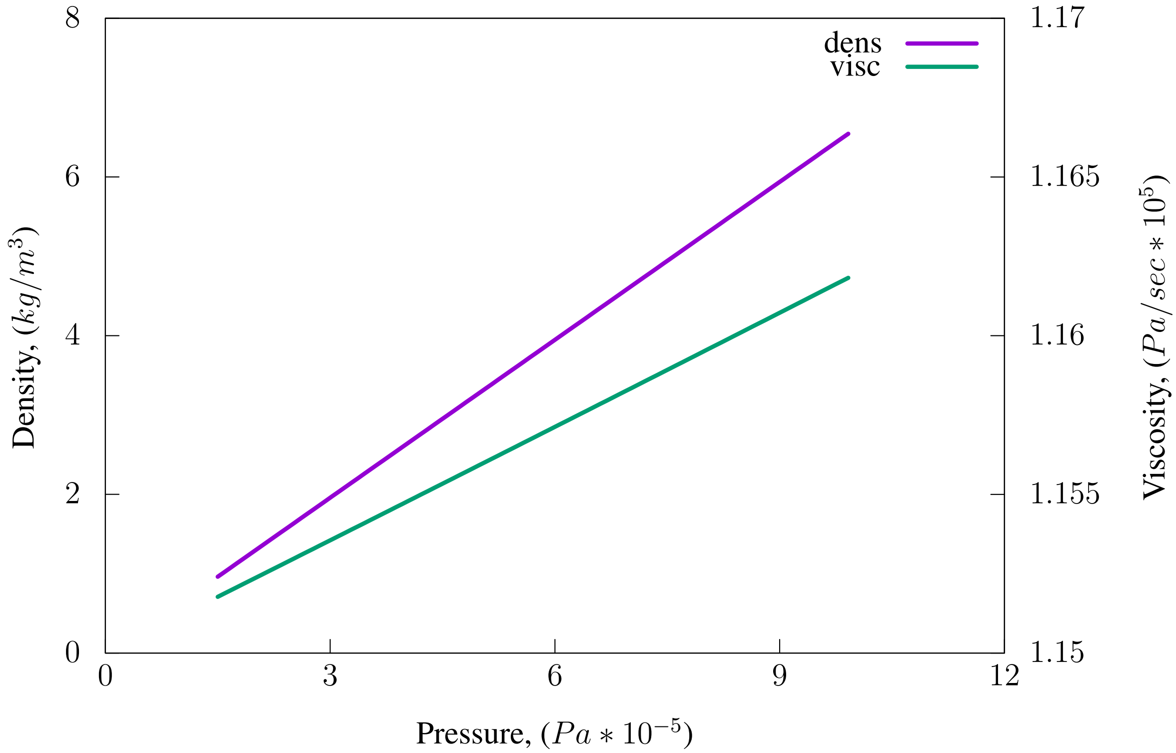

Figure 2: Methane density and viscosity approximations.

Two different experiments are made under steady-state and transient flow conditions. The core sample is the same for the both cases. The confining pressure should be constant throughout the whole experiment (**???**) and the outlet valve is fully opened. Such experiments are repeated using two different gases - helium and methane. Please refer to Fig. 3 and Fig. 4 for helium and to Fig. 5 and Fig. 6 for methane.

Considering a steady-state flow, the inlet pressure is gradually decreased by using a mass flow controller. As can be seen, for instance, from Fig. 3, the pause in the pressure drop immediately leads to the correspondent flow rate response. Thus, the characteristic time of relaxation is minimal allowing to assume the steady-state nature of a flow at the particular time step.

Regarding the transient flow, the pressure and the flow rate equilibration is established naturally with no external influence (see Fig. 4).

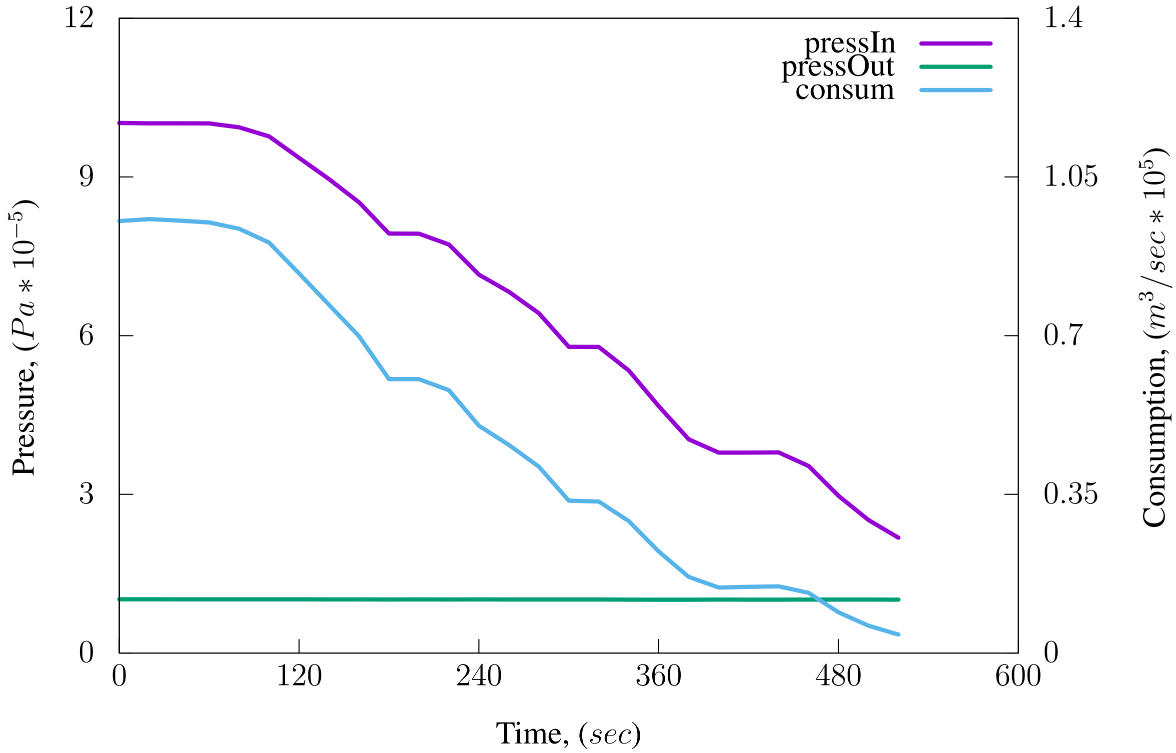

Figure 3: Helium steady-state.

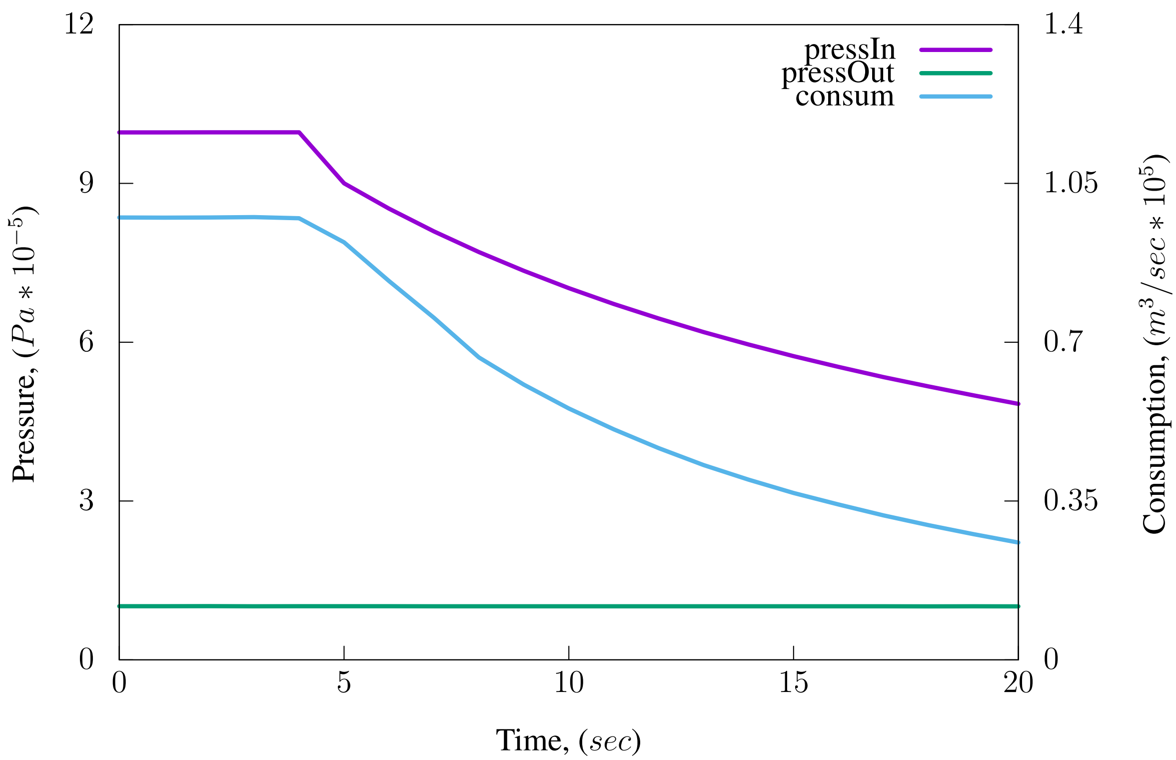

Figure 4: Helium unsteady-state.

See Fig. 5 and Fig. 6 for methane experiments.

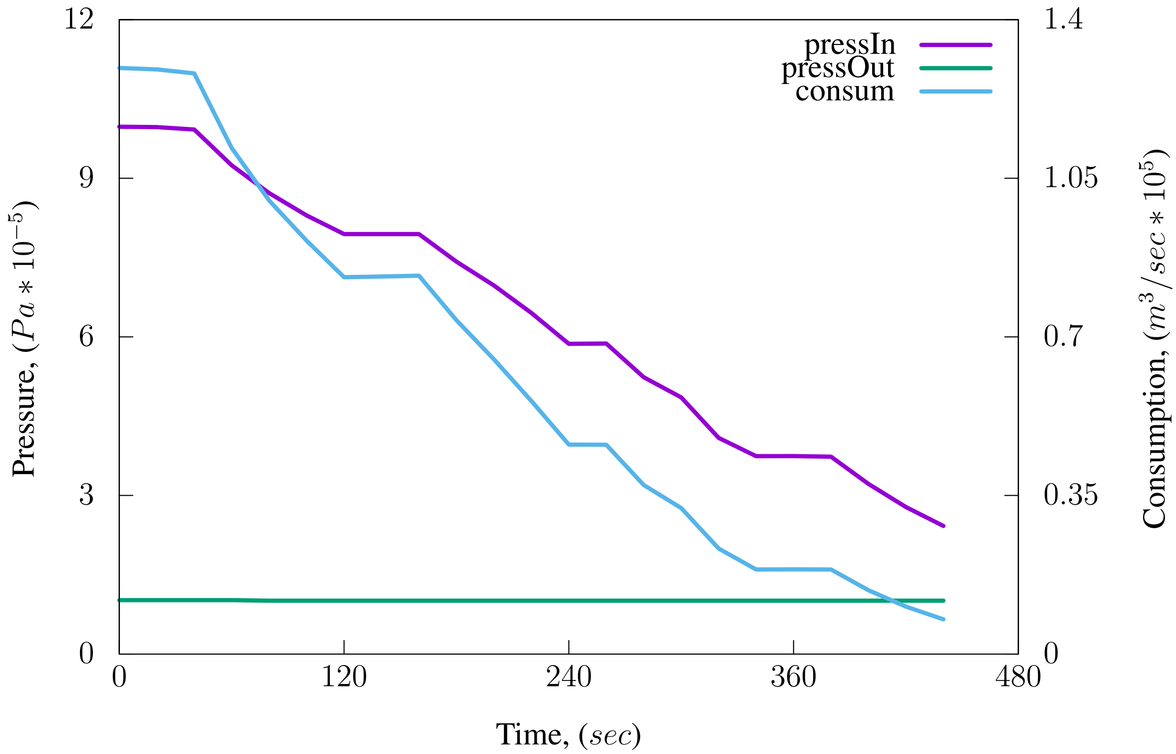

Figure 5: Methane steady-state.

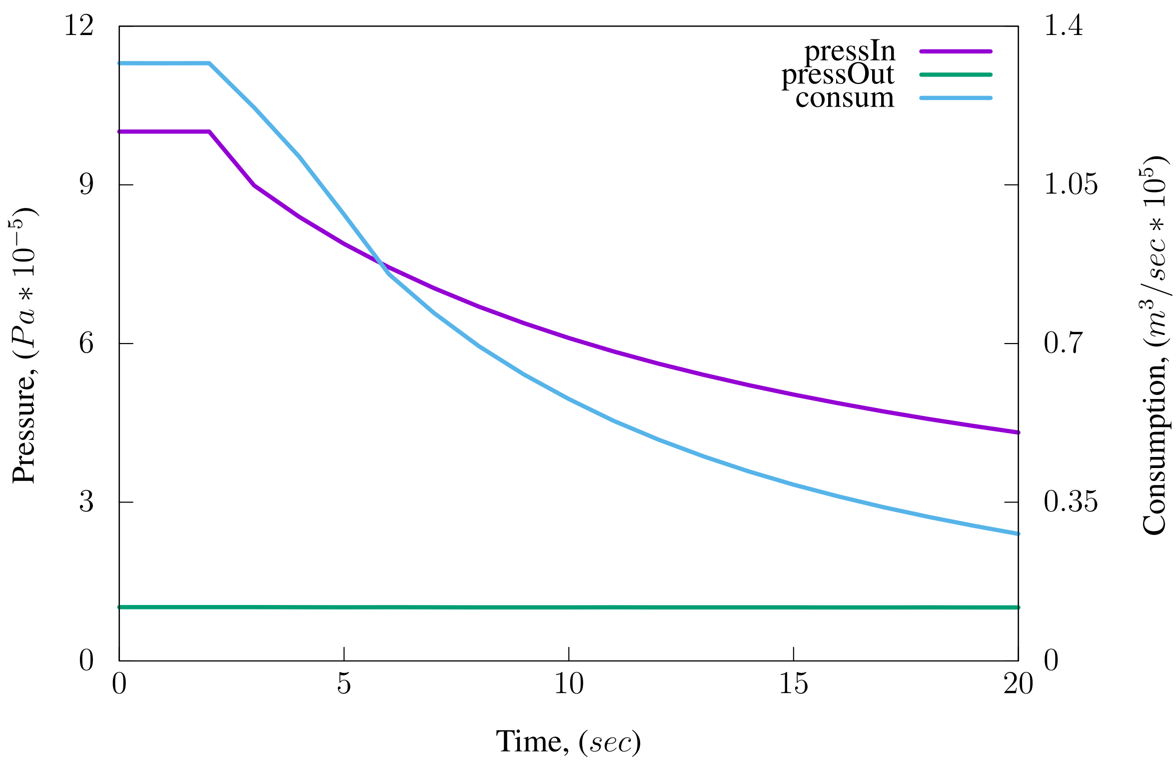

Figure 6: Methane unsteady-state.

The algorithm of permeability estimation using the flow parameter matching might be described by the following steps:

1. The range at which the permeability profile may vary during the steady-state experiment is assumed.
2. The adapted shooting method [4, 5] is used to select the particular functions 'permeability vs. pressure' which are further used in unsteady-state numerical simulations.
3. Out of the obtained numerical simulations, the one providing the higher match is chosen as desired.

The first stage of the numerical simulation allows to obtain the functional relationship between coal permeability and pore pressure based on the steady-state experiment. It is assumed that such an experiment represents the sequence of steady-state regimes at every measured time step. Thus, at each of these time steps, the permeability value correspondent to the particular pore pressure might be found using the described above matching method (see Fig. 7).

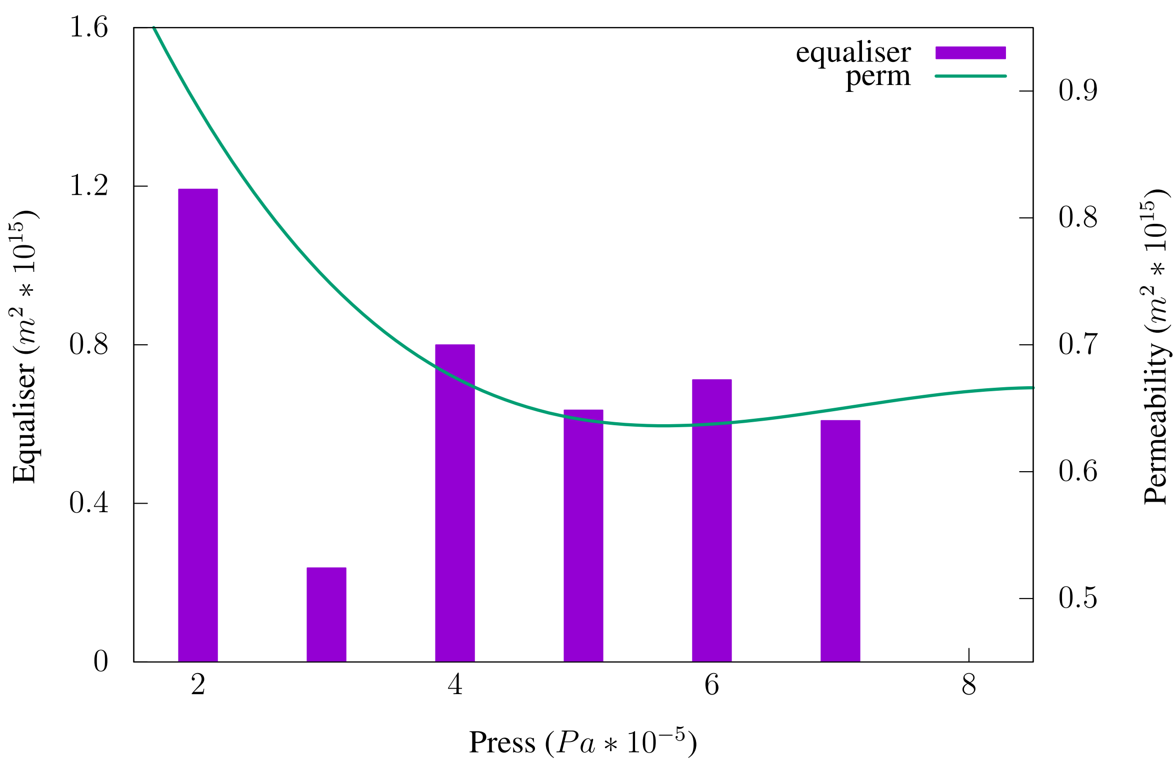

Figure 7: Helium permeability obtained from steady-state (green line) experiment.

Knowing the 'permeability vs. pressure' functional relationship, the experimental and numerical flow-rates can be compared ensuring the validity of the obtained function as can be seen in Fig. 8.

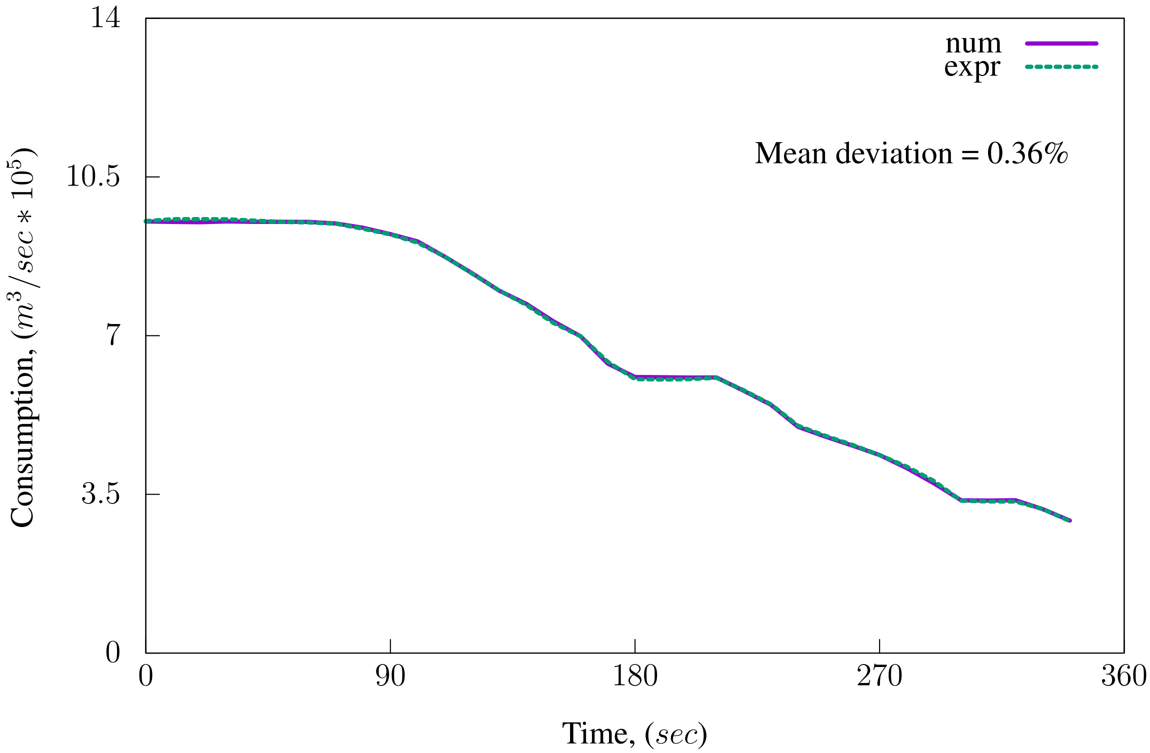

Figure 8: Helium steady-state numerical and experimental consumptions.

Having the functional relationship between coal permeability and its pore pressure obtained from the steady-state experiment, it can be further used in the unsteady-state experiment. As porosity also changes with pressure under transient flow conditions, the laboratory data is matched with the numerical simulation (see Fig. 12).

The matching is executed by changing the coefficients in the assumed polynomial relation between coal pore pressure and its porosity (see Fig. 11). The matching is utilised using self-developed numerical algorithm with in-built Ceres-Solver [6] further called 'Equaliser'. In order to achieve the best match, one may adjust the 'Equaliser' settings. The parameters which might be manually changed are the number of approximation points used for curve filling and the total number of iterations (see Fig.9). The 'Equaliser' numerical algorithm is non-trivial and will be described in more details later in the manuscript.

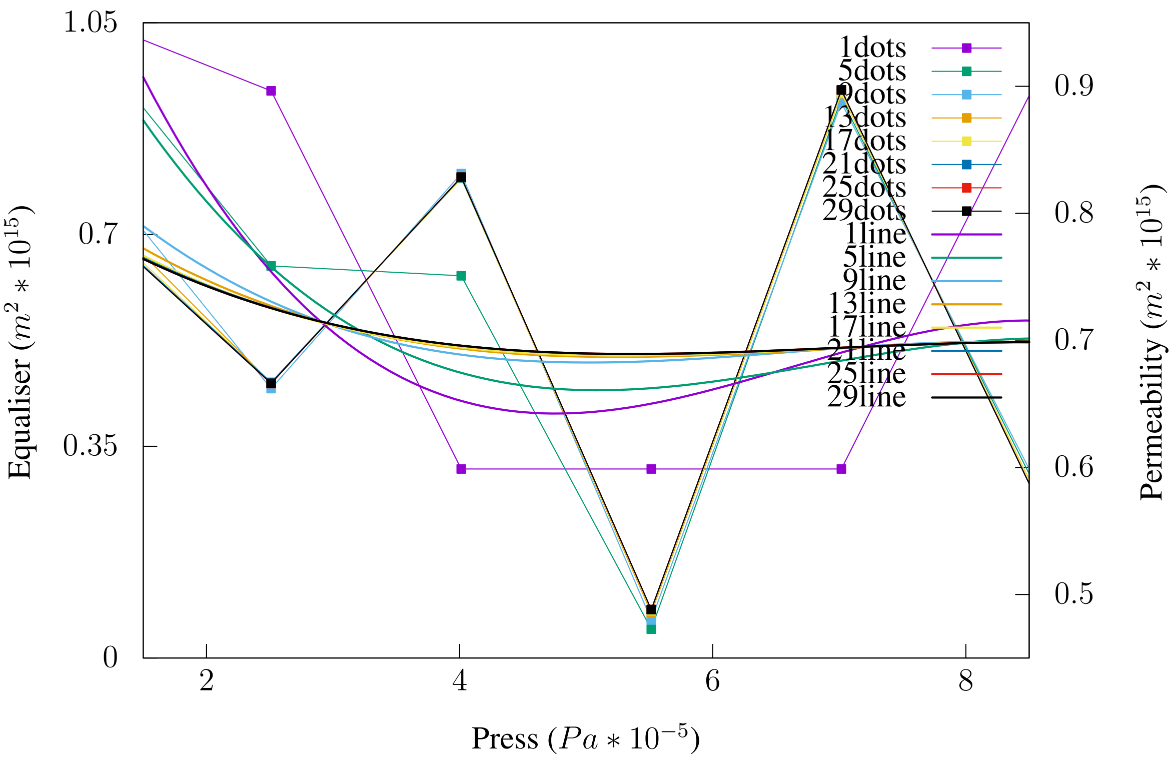

Figure 9: Equaliser working algorithm

As can bee seen from Fig. 12 there is a considerable mismatch between the numerical and experimental flow rates at the beginning of the transient experiment. Such an issue may occur due to:

1. The laboratory obtained flow rates at the beginning of steady-state and transient experiments are not equal. These flow rates should be equal as the pressure difference, flowing gases, core and the whole experimental set-up are kept the same. Nevertheless, all the experimental data has such an issue depicted in Fig 10. Importantly, the outlet pressure for the whole set of experiments is atmospheric, so the outlet valve is kept opened. Despite the steady-state experiment has slightly higher inlet pressure than the unsteady-state experiment, its flow rate is considerably lower.

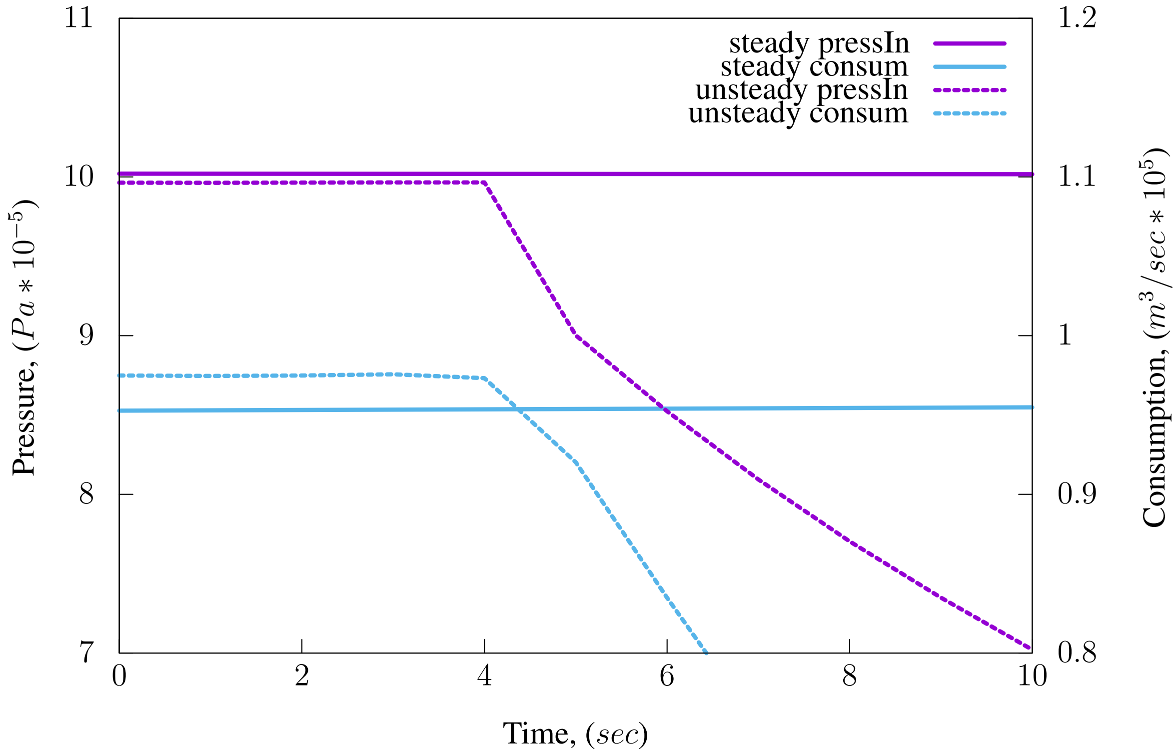

Figure 10: Comparison of initial stages during helium steady- and unsteady-state experiments.

2. The only factor logically explaining such situation might be the **confining pressure** which may differ from one experiment to another. Unfortunately, **the confining pressure data was not reported**, so we cannot check the stability of confining pressure. Even a **slight variation in the confining pressure** during the experiment or from one experiment to another **may lead to significant errors in porosity determination**.

3. The permeability matching works better due to several reasons, such as higher sensitivity of the flow rate to permeability in comparison with porosity, and the steady-state nature of the permeability experiment (slower rate of pore pressure decline).

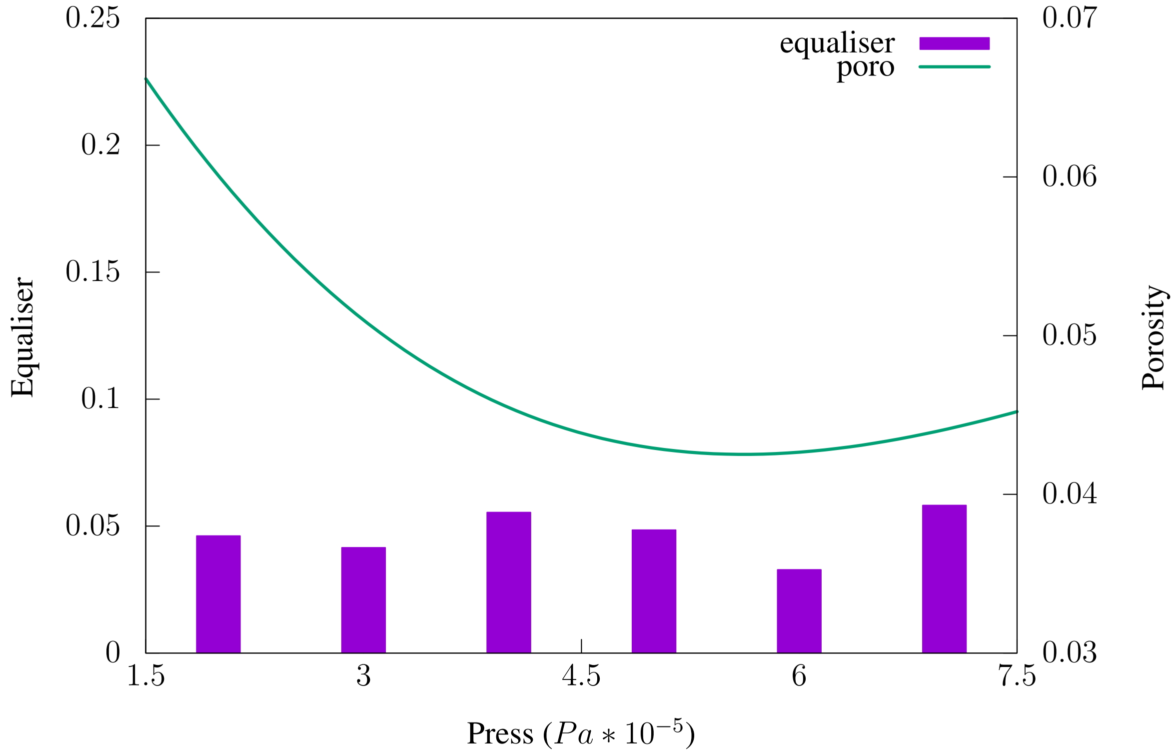

Figure 11: Effective porosity obtained by Equaliser using steady-state permeability.

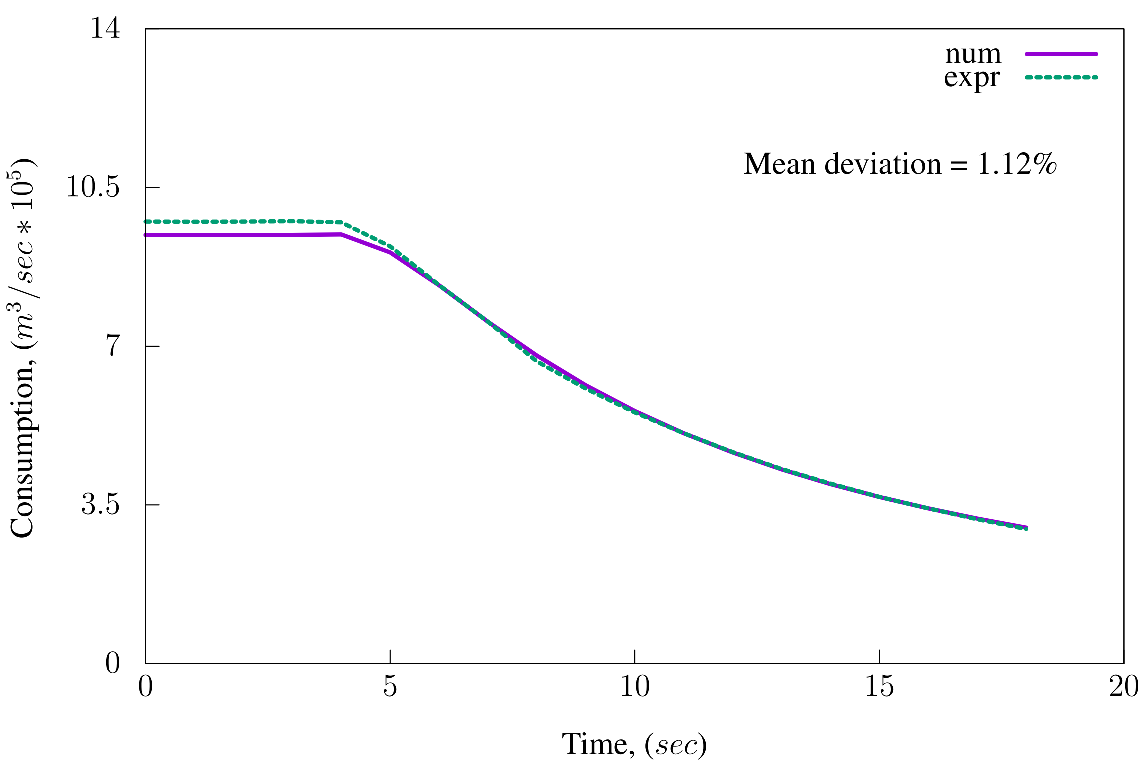

Figure 12: Helium numerical and experimental consumptions with steady-state permeability and unsteady-state porosity.

The results for coal permeability and porosity with methane as a flowing gas are presented below. The 'permeability vs. density' relation is obtained form the steady-state experiment (see Fig. 13), the sufficient match between steady-state numerical and laboratory experimental data is clearly achieved (see Fig. 14).

The 'permeability vs. porosity' relation is obtained from the unsteady-state relation (see Fig. 15), the undesirable mismatch between unsteady-state numerical and laboratory experimental data is visible (see Fig. 16). The reasons for such an issue was described above when exploring the helium case. Notably, the conducted numerical experiments for methane provide a better match with the laboratory data compare to the helium results.

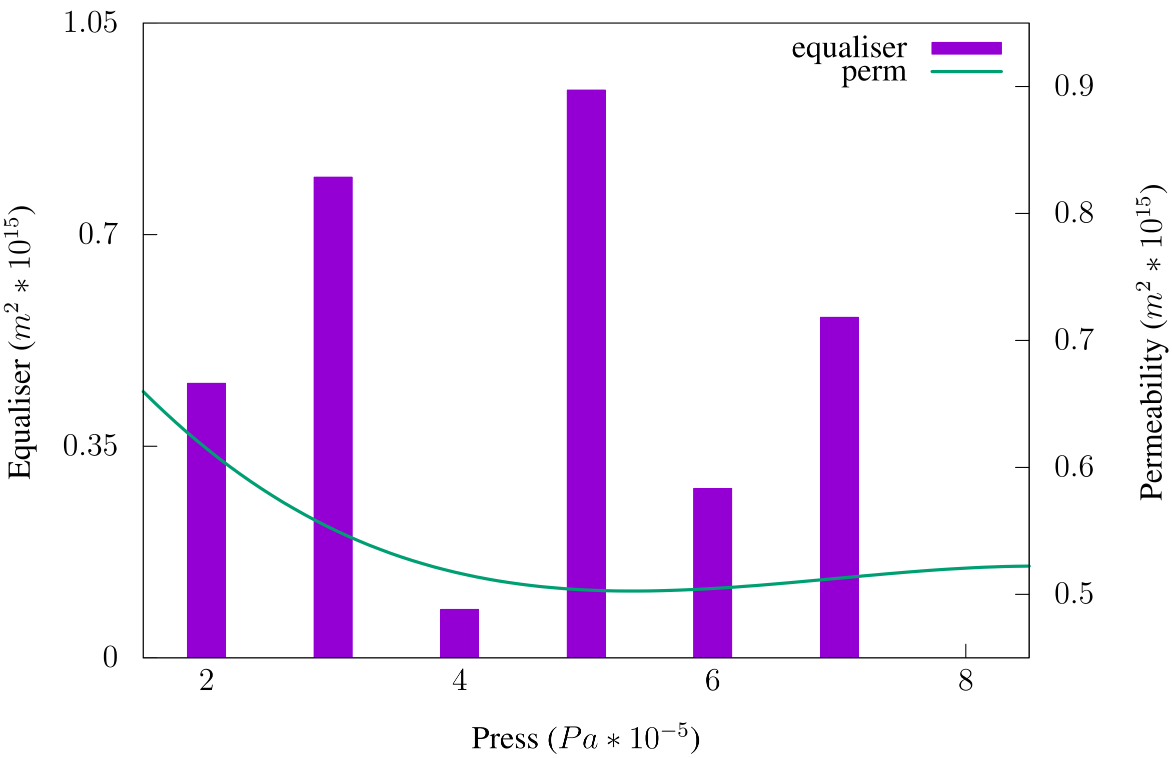

Figure 13: Methane steady-state permeability .

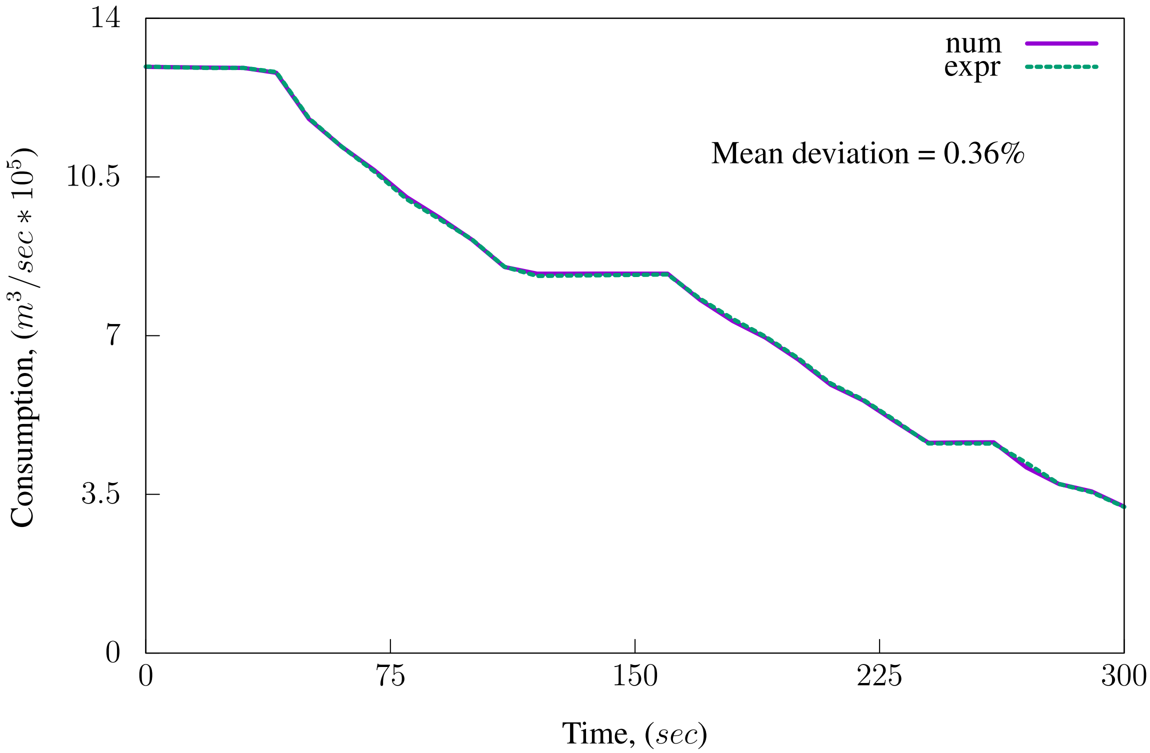

Figure 14: Methane steady-state numerical and experimental consumptions.

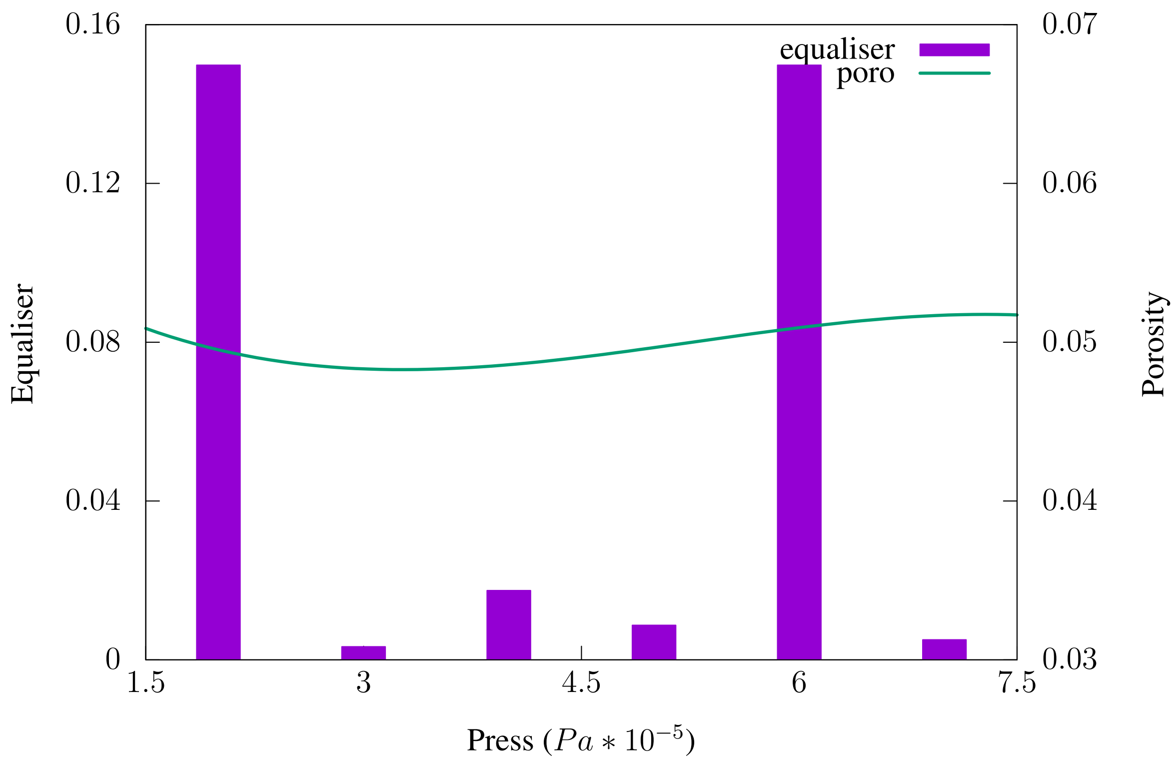

Figure 15: Methane effective porosity obtained by Equaliser using steady-state permeability.

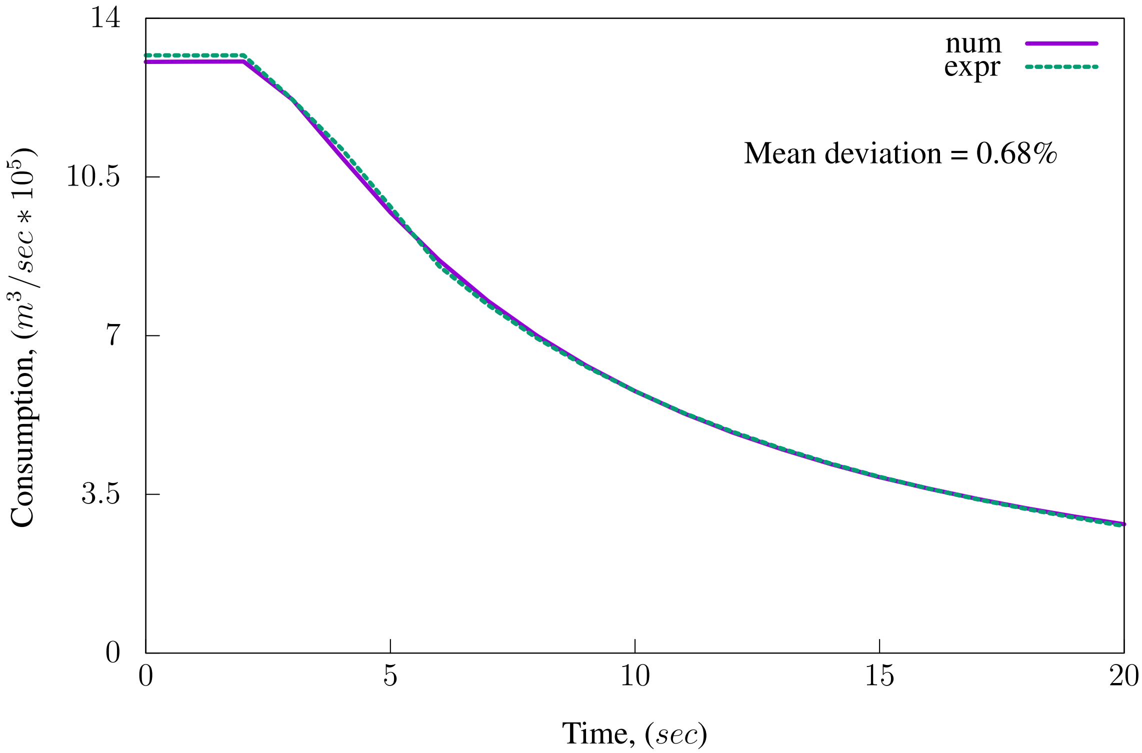

Figure 16: Methane numerical and experimental consumptions with steady-state permeability and unsteady-state porosity.

CONCLUSIONS AND RECOMMENDATIONS

Based on the research finding and some additional issues raised above, several conclusions and recommendations can be made. The proposed matching method may accurately estimate the functional relationship between the pore pressure and rock permeability under steady-state conditions. The dynamic effective porosity may also be estimated with sufficient precision, however several adjustment in the experimental process might be made:

1. Redo methane and helium steady-state and unsteady-state experiments with accurate control over confining pressure. If the confining pressure drops throughout the experiment, it should be manually increased using hydraulic pump. The confining pressure has to be also recorded in the text or excel file.

2. As the core sample used looks damaged, it would be helpful to use the one which is better prepared if possible. Large chips on the edges of the sample may lead to the overestimated porosity values.

3. It might be helpful if flow rate and pressure data sets have equal recorded time steps dt (it is easily adjusted using available software).

References

[1] Helge Petersen. The properties of helium: density, specific heats, viscosity, and thermal conductivity at pressures from 1 to 100 bar and from room temperature to about 1800 k. Technical report, 1970.

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[3] D. Y Peng and D.B Robinson. A new two-constant equation of state. Industrial & Engineering Chemistry Fundamentals, 15(1):59–64, 1976.

[4] David D Morrison, James D Riley, and John F Zancanaro. Multiple shooting method for two-point boundary value problems. Communications of the ACM, 5(12):613–614, 1962.

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[6] Sameer Agarwal, Keir Mierle, and Others. Ceres solver. `http://ceres-solver.org`.