Task 3.1

Title

Innovative technologies

Projects (presented on the following pages)

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Understanding the unstable off-design operation of Francis turbines for large scale NRE integration
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Prediction of hydro-acoustic resonances in hydropower plants operating in off-design conditions
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Extension of Francis turbine Operating Conditions by Controlling the Part Load Vortex Rope
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Development of an experimental protocol to assess the new kinetic turbine performance
S. Richard, A. Gaspoz, V. Hasmatuchi, N. Brunner, S. Chevailler, C. Münch-Alligné

Expected Corrosion Issues in Geothermal Power Plants in Switzerland
A. Vallejo-Vitaller, U. Angst, B. Elsener
**DuoTurbo: Mechanical Design**

D. Biner¹, S. Luisier¹, L. Rapillard¹, L. Andolfatto², V. Berruex², V. Hasmatuchi¹, F. Avellan², C. Münch-Alligné¹

¹HES-SO Valais/Wallis, School of Engineering, Hydroelectricity Group, Sion, daniel.biner@hevs.ch
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**Context**

- Recovering hydraulic energy lost in drinking water networks
- Modular in-line “plug and play” turbine from 5 to 25 kW
- No environmental impact
- Low investment costs

**Technical challenges**

The hydraulic and electrical concepts of the DuoTurbo prototype have successfully been validated by laboratory tests in 2016. The main issue that is still not entirely resolved, concerns the mechanical concept of the runner bearings. The given operating conditions and requirements make it difficult to find suitable technical solutions.

**Operating conditions**

- High axial forces > 3 kW possible
- High rotational speed up to 3500 min⁻¹
- Pipeline pressure > 20 bar possible
- Water contaminated with abrasive particles

**Requirements**

- High efficiency
- Minimum maintenance
- Low production costs
- Reliability and general lifetime of > 5 years

**Tested mechanical concepts**

The accomplishment of the given requirements is crucial for the realization of an industrial DuoTurbo turbine. Therefore, different mechanical solutions have been analyzed, designed and tested.

**Concept: Water lubricated radial (1.1) and axial (1.2) ceramic ball bearings with high corrosion resistance.**

**Conclusion:** Successful for hydraulic and electrical laboratory tests (2016). Enlarged viscous friction and uncertain long time behaviour of submerged ceramic bearings.

**Concept: Axial hydrostatic bearing (4.1) and radial hydrodynamic plain bearing (4.2), ensuring low mechanical friction, low wear and low maintenance costs. Hydrostatic bearing supplied by water pipeline pressure. Requires considerable precision of mechanical assembly.**

**Conclusion:** Functionality of hydrostatic bearing validated on separate test rig. Low efficiency of labyrinth seals caused failure during laboratory tests, due to underestimated axial forces.

**Concept:** Encapsulated, grease lubricated angular ball bearings (5.1) guaranteeing requested lifetime and reliability. Tightness ensured by mechanical seal (5.2), typically used for pumps. Considerable maintenance costs due to regular replacement of the seal (1-2 years).

**Actual state:** First laboratory performance tests successful. Endurance test phase ongoing until end of 2017.

**Development team of Duo Turbo (CTI Nr. 171971 PFEN-IW)**

HES-SO Valais/Wallis:

EPFL LMH:
L. Andolfatto, V. Berruex, F. Avellan

Industrial partners:
Telsa SA, Jacquier-Luisier SA, Valelectric Farner SA

**References**


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**Notes:**
- CTI Nr. 171971 PFEN-IW
- ENR / exploit Swiss Family of modular ERS / exploit Swiss energy recovery
- Project: Water lubricated radial ceramic ball bearings (2.1) combined with hydrodynamic radial plain bearing (2.2). Reduced mechanical losses and production costs.
- Conclusion: Advanced stage of wear of ceramic ball bearings after laboratory tests. Water lubrication insufficient to ensure requested reliability.
- Concept: Hydrodynamic axial and radial plain bearings (3.1), ensuring low wear, low mechanical friction, low maintenance and production costs.
- Conclusion: Different bearing materials and shapes tested on a test rig. Hydrodynamic effect too weak to support axial load of turbine runners. Failure during laboratory tests.
- Concept: Axial hydrostatic bearing (4.1) and radial hydrodynamic plain bearing (4.2), ensuring low mechanical friction, low wear and low maintenance costs. Hydrostatic bearing supplied by water pipeline pressure. Requires considerable precision of mechanical assembly.
- Conclusion: Functionality of hydrostatic bearing validated on separate test rig. Low efficiency of labyrinth seals caused failure during laboratory tests, due to underestimated axial forces.

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**Graphical Elements:**

- Modular concept
- Initial proof of concept
- Version 0.2
- Version 0.3
- Version 0.4
- Version 0.5

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**Diagram:**

- DuoTurbo turbine
- Runner Optimization
- Context
- Technical challenges
- Operating conditions
- Requirements
- Tested mechanical concepts
- Conclusion
- References
 Workflow for managing deep deviated geothermal well stability

Asmae Dahrabou(1), Benoît Valley(1), Florentin Ladner(2), Frédéric Guinot(2), Peter Meier(2)
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(2) Geo-Energie Suisse AG, Reitergasse 11, 8004 Zürich, Switzerland.

I- Project context and objectives

In the frame of a CTI-project, the CHYN and Geo-Energie Suisse AG are developing a workflow and associated software tools that allow a fast decision-making process for selecting an optimal well trajectory while drilling deep inclined wells for EGS-projects. The goal is to minimize borehole instabilities as it enhances drilling performance and maximize the intersection with natural fractures because it increases overall productivity or injectivity of the well. The specificity of the workflow is that it applies to crystalline rocks and includes an uncertainty and risk assessment framework.

II- Workflow development approach

A sensitivity study performed on data from the well BS-1 (DHM project Basel) showed that the most influential parameters on borehole stability are the magnitude of the maximum horizontal stress, SHmax the uniaxial compressive strength, UCS, and the internal borehole pressure Pmud.

2.1- Model calibration

The understanding of borehole failure in deep crystalline well is lacunary because the strength and stress parameters are largely unknown independently. Moreover, there is no agreement on the appropriate failure model required to capture all characteristics of borehole failure

a. Calibration based on simple but consistent failure modeling approach

Different failure criteria were tested and it was shown that the purely cohesive criterion allows getting calibration that is more consistent across the studied failure indicators. This result is consistent with the literature that indicates that breakout formation is a cohesion weakening process.

b. Calibration based on independent data (sonic and density)

Figure 1. a) Failure observation in BS-1 hole at z=3509m. The blue circle corresponds to the bit size and the black envelop represents the geometry of the well. An average value of w= 92°, d= 56.36mm, CSA= 657.26 cm² were observed for breakout width, depth and the cross sectional area respectively, b) Predicted failure using Mohr-Coulomb criterion in a simple elasto-brittle computation, c) Calibrated couples (SHmax,UCS), for a vertical hole at z=3509m using the purely cohesive failure

Figure 2. Output from the strength evaluation computations. This evaluation is performed in two main steps: a) realistic parameters ranges are computed based on frictional strength limit of the earth crust and observation of tensile failure in the well, then c) the strength is approximated using strength proxy and the strength/stress couple is calibrated.

Figure 3. Computed extrapolated profiles of SHmax and UCS

2.2- Selection of wellbore trajectories scenarios

A summary of many decision factor in terms of stereographic projection is presented in order to help selecting potential scenario to be tested

Figure 4. A set of stereographic projections in terms of many decision factors (Breakout width, breakout depth, slip tendency, dilation tendency and fracture frequency) that help selecting potential scenario. These results were performed for depth= 3500m, SHmax= 116 MPa, Sv= 87.2 MPa, Shmin= 66.5 MPa, Pp= 34.3 MPa. Four scenarios with different borehole orientation were selected (white points shown in the stereoplots)

III- Conclusions

• UCS and SHmax (maximum horizontal principal stresses) are the parameters the most influential on failure computation.
• In combination with an elastic solution for the computation of the stress concentration around the borehole, a purely cohesive failure criterion provides the most consistent prediction across failure indicators
• A pragmatic calibration approach was chosen: firstly, realistic ranges for both SHmax and UCS were computed based on admissible stress limits and secondly, independent data (sonic and density data) were used as a proxy to approximate the strength

IV- Perspectives

• Further develop the calibration approach adding some additional important parameters like well stability control with drilling mud
• Bring in some more systematic approach in selecting scenario based on identification of key drilling scenario using clustering analyses
• Further test and develop the simple failure model used so far against more advanced modeling approach
• Further test the workflow on existing deep geothermal drilling dataset (Soultz…) and to new deep geothermal drilling site (Haute-Sorne)

References

Prediction of hydro-acoustic resonances in hydropower plants operating in off-design conditions

A. Favrel, J. Gomes, C. Landry, S. Alligné, C. Nicolet and F. Avellan

Context
Unsteady power output from renewable energies
Electrical grid is exposed to large fluctuations
Balancing by off-design operation of hydropower plants
High swirl and unstable cavitation flows

Research Project
The HYPERBOLE research project (ERC FP7-ENERGY-2013-1-Grant 608532), consisting of leading European universities and turbine manufacturers, aims at making a decisive contribution towards the smooth integration of NRE by enabling the safe extension of Francis turbines operating range.

Objectives:
- Develop advanced 1D numerical model of cavitation flows in the draft tube of Francis turbines operating in off-design conditions
- Develop a complete methodology for predicting hydro-acoustic resonances in hydropower plants based on 1D numerical modelling and reduced scale model tests

Methodology
Reduced scale model test in laboratory
- Identification of the precession frequency and the natural frequency for a given $\sigma$ – value and Froude number
- Identification of the precession frequency and the natural frequency for a given $\sigma$ – value and Froude number
- Influence of both the head and discharge on the precession and natural frequencies represented by a single parameter, the swirl number [2]:

$$\frac{Q}{Q_{ref}} = \frac{\pi}{2} \left( \frac{Q}{Q_{ref}} \right)$$

- Identification of hydro-acoustic parameters [1]
  - Wave speed in the draft tube at the model scale as a function of the swirl number:

- 1D model of hydraulic test rig in off-design conditions [1]
- 1D model of hydraulic test rig in off-design conditions [1]

Full-scale hydropower plant
Prediction of resonance conditions on the prototype
- Direct transposition of the precession frequency from model to prototype
- Computation of the prototype natural frequencies with 1D SIMSEN model of the hydropower plant unit
- Determination of the output power in resonance conditions, i.e. when $f_0 = f_{pre}$

Results and validation by on-site measurements
- Very good agreement between predicted and experimental values for both the precession and natural frequencies, as well for the output power in resonance conditions

References
Understanding the unstable off-design operation of Francis turbines for large scale NRE integration
A. Favrel, K. Yamamoto, A. Müller, C. Landry and F. Avellan

Context

Unsteady power output from renewable energies
Electrical grid is exposed to large fluctuations
High swirl and unstable cavitation flows

Flow instabilities in off-design conditions

Francis turbine units operating in off-design conditions experience the development of flow instabilities, inducing cavitation and periodical / stochastic pressure pulsations in the hydraulic system:

FULL LOAD:
Self-oscillation of an axisymmetric cavitation vortex rope in the draft tube inducing pressure, torque and power pulsations

PART LOAD:
Precession of a cavitation vortex rope in the draft tube acting as a pressure excitation source with risk of resonance

DEEP PART LOAD:
Cavitation vortices in the inter-blade channels (inter-blade vortices) with unknown draft tube flow interaction and erosive potential

References


Research Project

The HYPERBOLE research project (ERC/FP7-ENERGY-2013-1-Grant 608532), consisting of leading European universities and turbine manufacturers, aims at making a decisive contribution towards the smooth integration of NRE by enabling the safe extension of Francis turbines operating range.

Objectives:

- Reach a profound understanding of the underlying physical mechanisms leading to an unstable behaviour of hydropower unit operating in off-design conditions
- Enhance the accuracy of existing models for a comprehensive simulation of hydroelectric power plants over their whole operating range.

Investigative approach & Results

2D-LDV to determine the flow velocity fluctuations and identify the unstable fluid-structure interaction mechanisms at full load

2D-PIV to identify the influence of the flow discharge on the vortex structure and parameters at part load

Visualizations with instrumented guide vanes & CFD simulation to capture the inter-blade vortices at deep part load
Performance assessment of a new kinetic turbine prototype

A. Gaspoz¹, S. Richard¹, V. Hasmatuchi¹, N. Brunner², C. Münch-Alligné¹

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²Stahleinbau Gmbh, Talstrasse 30, CH-3922 Stalden, Switzerland

Objectives of this “pilot & demonstrator” project

• Design and construction of a first prototype of isokinetic turbine for artificial channels with a power of 1 kW
• Evaluation of its hydraulic performances in the tailrace canal of the Lavey run-of-river powerplant (Rhône river)
• Validation of the numerical simulation results
• Preparation of an industrialization phase to exploit this energetic potential in Switzerland and abroad

Pilot site

The pilot site to assess the performance of the first prototype is the tailrace canal of the run-of-the-river Lavey Hydropower plant in Switzerland. At the end of 2016, the open-air platform and the turbine have been installed in the tailrace channel.

Numerical investigations

Unsteady multiphase homogeneous flow numerical simulations of the turbine in the tailrace channel of Lavey have been performed using the ANSYS CFX software. The incompressible Reynolds Averaged Navier–Stokes equations are solved using a finite volume approach. The set of equations is closed-formed and solved using a two-equation turbulence model: the Shear Stress Transport (SST) model. A hybrid mesh of 13 Millions of nodes is used.

The numerical results have shown that the turbine has no impact on the available head of the Lavey powerplant. Moreover the Venturi effect of the duct and the specific design for the runner induce a strong acceleration of the flow inside the machine, as expected [1].

Experimental investigation

To measure the performance of the kinetic turbine on the pilot site, a specific instrumentation has been set up [2]:

• Acquisition/control system
• River boat equipped with an ADCP system
• Electrical multimeter
• Onboard instrumentation

Performance assessment

The turbine performance is obtained by measuring the produced electrical power compared to the available hydraulic power [3]. The objective of the project to reach 1kW with the turbine has been largely outshined with a maximal electrical power measured of 15 kW.

Conclusions and perspectives

These investigations have shown that:

• The objective of the project to produce 1kW with a new prototype of a kinetic turbine has been reached.
• Unsteady two phase flow numerical simulations allow to predict performance fairly accurately at BEP.
• The next step is the installation of a farm of kinetic turbines to investigate the influence of the machines between each other.

Acknowledgements

References

Empirical models for Francis turbine performance estimation

J. Gomes, L. Andolfatto, F. Avellan

Motivation

- The Energy Strategy 2050: more energy generation from renewable sources;
- In Switzerland, many hydropower plants can be upgraded or rehabilitated, therefore generating more power with the same amount of water [1];
- Many feasibility studies, such as those for upgrading or rehabilitating the power plants, take the turbine’s efficiency as a constant and don’t check off-design or transient conditions.
- Being able to properly evaluate these other conditions and optimize the project from the very beginning is the added-value of this research work.

Methods

- Representing the efficiency as a set of parameters [2]

\[
\begin{bmatrix}
\lambda_1 \\
\lambda_2 \\
\vdots \\
\lambda_n
\end{bmatrix}
= \sum_{i=1}^{n} \lambda_i \cdot \phi(Q_n, N)
\]

- For better precision, more complex efficiency surfaces may be achieved through a combination of low order polynomials and weighting functions.

Available test data used to train the empirical models

References


Generating efficiency estimation curves in 4 steps:

1-Peak Efficiency Estimation: based on an adaptation of a model developed by Gordon, J.L. [3], the peak efficiency \( \eta_{BEP} \) is estimated according to the turbine’s year of commissioning, size and specific speed.

2- Typical operation zone: empirical model. Curves are adjusted according to the turbine’s specific speed.

3-Runaway curve: empirical model. Curves are adjusted according to the turbine’s specific speed.

4- Transition zones: low order polynomials combined with weighting functions make the transition between runaway and operating zone values.

Conclusion

By means of a combination of empirical models trained with data obtained from efficiency measurements of Francis turbines through a span of almost a hundred years [3], a methodology has been developed aimed to predict the performance of Francis turbines.

Inside the RenovHydro Project, an optimization loop that searches for the most suitable design parameters of the future Francis turbine.

A very good agreement has been observed between predictions and measurements, both for steady, typical operating conditions and for simulations of transient conditions such as an emergency shutdown.
Impact of polymers in well cementing for geothermal wells

M. Palacios, R. K. Mishra, D. Sanz-Pont, R. J. Flatt*

1. Introduction
Backfilling with cementitious material is essential for mechanical stability of deep wells. However, with increasing depth temperature rises involving many technological challenges such as poor rheological properties and quick setting of cement slurries. On site, a combination of different chemical admixtures including dispersants, set retarders and accelerators are normally used although a loss of performance is often found.

In the Group of Physical Chemistry of Building Materials, in the frame of WP3 Task 3.1 “Geo-energy technologies”, we investigate the use of specific comb-copolymer superplasticizers to control cement hydration kinetics and rheological properties of cement slurries at the extreme conditions encountered in geothermal well. This will be done using an experimental and molecular modeling approach.

2. Methods
- Isothermal calorimetry to study the impact of polymer structure and dosage on cement reaction kinetics with the temperature.
- Inductively Coupled Plasma – Optical Emission Spectrometry (ICP-OES) and Dynamic Light Scattering (DLS) to analyze cement pore solutions.
- High-end rheometer to investigate the rheological properties of the superplastized retarded mixes.
- MD simulation to understand the interaction between organic admixtures and the chemical species present in solution.

3. Highlights of the project
It has been demonstrated for first time that cement hydration can be delayed at high temperatures by specific dosages and structures of comb-copolymer superplasticizers (Figure 1).

The analysis of the chemical composition of the cement pore solution using ICP-OES method[1] has proved a dramatic increase in the concentrations of Si, Al, Fe and Mg, in admixed cement pastes hydrated at 23 °C (Figure 2). The formation of polymer aggregates involving intramolecular complexes between polymers and multivalent cations could explain the increase of these elements.

4. Ongoing research
The following studies will give new insights into the design of more robust cement grouts:
- Role of complex formation between polymer and multivalent (Al, Mg and Fe) cations
- Influence of the temperature on the adsorption of the polymer.
- Impact of PCE admixtures in presence of Mg and Fe ions

References
Extension of Francis Turbine Operating Conditions by Controlling the Part Load Vortex Rope

Pasche S., Gallaire F., Avellan F.

Problematic

This project consists of applying the latest flow control theories to an important issue arising in hydraulic turbines: the development of a cavitation vortex rope at part load conditions in Francis turbines.

With the future massive introduction of renewable energy in the distribution systems, the operation of Francis turbines at off-design conditions, such as the part load regime, is thought to be one of the main solutions to mitigate large power fluctuations of the grid.

An intense cavitation rope is however known to appear in these conditions, which produces large pressure fluctuations at a well-defined frequency, with the associated hazards induced by the risks of operating instability and fatigue and resonance of the mechanical structures.

Objectives

Control the part load vortex rope to enable the extension of Francis turbine operating conditions and to further enhance the power generation flexibility of these generating units.

Methods

Since the part load vortex rope is identified as an unstable eigenmode, a flow control strategy aiming at stabilizing this spatially developing mode is applied to obtain an optimal volume force controlling the part load vortex rope.

Results

A new fluid flow control strategy aiming at stabilizing the development of self-sustained instabilities is applied to the Francis turbine vortex flow operating at part load conditions. This approach has led to the determination of the amplitude and the location of an optimal volume force, which successfully controls the part load vortex rope and can be, in a future work, realized by a passive control appendage. The enhancement of operation flexibility of Francis turbine is therefore numerically achieved in this project, which sheds a new light in the potential development of hydraulic turbines in mitigating electric power fluctuations.

Conclusion

Part load vortex rope

Controlled flow distribution

Transient wall pressure signal of the part load vortex rope control

Optimal volume force

Part load vortex rope eigenvalue spectrum and flow control strategy
Development of an experimental protocol to assess the new kinetic turbine performance

S. Richard¹, A. Gaspoz¹, V. Hasmatuchi¹, N. Brunner², S. Chevailler¹, C. Münch-Alligné¹

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²Stahleinbau GmbH, Talstrasse 30, CH-3922 Stalden, Switzerland

Context

- The first prototype of an isokinetic turbine for artificial channels with a power of 1 kW has been designed, optimised and manufactured [1].
- Its hydraulic performances have to be measured directly on a pilot site represented by the tailrace canal of the Lavey run-of-river powerplant (Rhône river) [2-3].

Objective:

- Development of an experimental protocol to assess the performance characteristics of the machine on the whole operating range using the available instrumentation.

Electro-mechanical concept

- Sealed bulb housing including the variable speed generator, the encoder, the speed multiplier and the mechanical coupling
- 1kW compact permanent magnet synchronous generator
- Coaxial gear speed multiplier with a factor of 1:16
- Mechanical shaft sealing: resistant to suspended sediment conditions

Performance tests of the generator

Main characteristics:

- Phase TK142-100-041-G-R0-pa synchronous machine
- 12 poles (permanent magnet)
- Water cooled
- Rated power: 2.39 kW
- Rated current: 6 A
- Rated/maximum speed: 1’000/2’000 rpm

Components of the testing bench:

- Testing generator
- Torquemeter & encoder
- Entraînement moteur unimotor fm142U2E300
- Emerson M700 frequency converters

Instrumentation:

- Magtrol TMB 208 torquemeter
- Heidenhein ECN 1325 encoder
- Zimmer LMG 670 precision multimeter

Electrical performances

- Torque-current constant
- Generator-gear box efficiency

Performance tests of the gear box

Experimental methodology:

- Generator-gear box tested together
- Specific system allowing up to 260 N m manual breaking torque
- Performance measurements based on synchronized dynamic acquisition of sensors signals

Instrumentation:

- NCTE 3000 torquemeter
- Heidenhein ECN 1325 encoder
- Zimmer LMG670 precision multimeter
- NI cDAQ-7124 signals digitizer

Main result:

- Dependency between the mechanical-to-electrical efficiency of the assembly generator-gear box and the measurements of the generator true-rms values of the current and the speed
- This methodology allows retrieving the hydraulic-to-mechanical efficiency of the turbine runner without torquemeter

Conclusions

- Performances of the electrical generator successfully measured
- Performances of the assembly between the electrical generator and of the gear box successfully retrieved using the dynamic method
- The established experimental protocol enables the performance measurements of the new isokinetic turbine prototype directly in the tailrace canal of the Lavey powerplant

Acknowledgements

References

1. Introduction

In Switzerland, the co-generation of electric power and heat from deep geothermal resources is gaining further attention. However, the expertise in operational issues and the knowledge of chemical properties of deep geothermal fluids (at depths of 4-5 km) is still limited. [1]

In this context, one of the main technical problems for the reliable and long-term operation of binary power plants is corrosion. Metallic materials, such as low-alloyed steels, are mainly subject to uniform corrosion, pitting corrosion, or stress corrosion cracking. The electrochemical reactions between the material and the environment lead to different types of corrosion products.

Therefore, the goal of this project is to contribute to a more detailed understanding of the corrosion mechanisms and the characterization of various metallic materials under various scenarios in Switzerland.

2. Experimental methods

An experimental setup consisting of a high temperature-high pressure test vessel has been used for the tests. The autoclave is heated from room temperature up to 200°C and subsequently cooled down. The heating and cooling cycles usually take ca. 15h.

Electrochemical techniques

The open circuit potential (OCP) is measured continuously during the tests with a multimeter Keithley 2701. Linear polarization resistance (LPR) measurements are performed at given temperatures (usually at 80, 120, 160, and 200°C) with a potentiostat Autolab PGSTAT302N. The corrosion rate is then calculated as given by the Faraday’s law:

\[
\text{Corrosion rate} = \frac{M \cdot i_{\text{corr}}}{z \cdot F \cdot \rho}
\]

Materials

The steel grade L80 Type 1 (0.25%C, 1.02%Mn, 0.45%Cr) is a typical low-alloyed steel used for the casing of wells and produced according to the API specification (American Petroleum Institute).

Synthetic fluids

Aqueous solutions were deaerated with N₂ gas for ca. 1-2h.

<table>
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<th>pH</th>
<th>Ca²⁺</th>
<th>Mg²⁺</th>
<th>Na⁺</th>
<th>K⁺</th>
<th>HCO₃⁻</th>
<th>SO₄²⁻</th>
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<td>0.0</td>
<td>375.0</td>
<td>300.0</td>
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</table>

3. Results

**Open Circuit Potential (OCP) evolution**

**Linear Polarization Resistance (LPR) measurements**

- Corrosion rates are lower during the cooling cycle
- Average corrosion rate is approx. 20µm/year

**pH value**

The pH value remains stable (8.2 ± 0.3 units) over the whole range of testing temperatures (20-200°C).

**SEM and EDX analysis after test**

4. Conclusions and future work

- The OCP does not vary significantly with temperature (-750mV vs. SCE). According to the Pourbaix diagram of iron, the obtained value suggests that this element is in the oxidation state Fe²⁺.
- Furthermore, the LPR measurements show that there is no dependency of the corrosion rate on temperature.
- From the SEM and EDX analysis, it can be seen that different oxides adhere to the metal surface (mostly carbonate components).
- Although the corrosion rate slightly changes with temperature (approx. 20µm/year), the corrosion behaviour of the material over longer time spans is still unknown. Further investigations on the protection provided by the corrosion products to the base metal are necessary.

5. References