pyEQL Documentation

Release v0.9.2

Ryan Kingsbury

Nov 07, 2023

CONTENTS

CONTENTS

DESCRIPTION

The goal of `pyEQL` is to provide a stable, intuitive, easy to learn python interface for water chemistry that can be connected to a variety of different modeling engines

Specifically, `pyEQL` defines a `Solution` class to represent an aqueous electrolyte solution. Virtually all of the user-facing functions in `pyEQL` are accessed through the `Solution` class. It also includes a number of other utilities to support water chemistry analysis including a database of diffusion coefficients, activity correction parameters, and other data on a variety of common electrolytes.

1-MINUTE TUTORIAL

2.1 Install

```
pip install pyEQL
```

2.2 Create a Solution

```python
>>> from pyEQL import Solution
>>> s1 = pyEQL.Solution({'Na+':'0.5 mol/kg', 'Cl-': '0.5 mol/kg'},
                        pH=8,
                        temperature = '20 degC',
                        volume='8 L')
```

2.3 Get properties

```python
>>> s1.density
<Quantity(1.03710384, 'kilogram / liter')>
>>> s1.conductivity
<Quantity(8.09523295, 'siemens / meter')>
>>> s1.osmotic_pressure.to('atm')
<Quantity(46.7798197, 'standard_atmosphere')>
>>> s1.get_amount('Na+', 'ug/L')
<Quantity(22989769.3, 'microgram / liter')>
```

KEY FEATURES

pyEQL is designed to be customizable and easy to integrate into projects that require modeling of chemical thermodyanmics of aqueous solutions. It aspires to provide a flexible, extensible framework for the user, with a high level of transparency about data sources and calculation methods.

- Build accurate solution properties using a minimum of inputs. Just specify the identity and quantity of a solute and pyEQL will do the rest.

- "Graceful Decay" from more sophisticated, data-intensive modeling approaches to simpler, less accurate ones depending on the amount of data supplied.

- Not limited to dilute solutions. pyEQL contains out of the box support for the Pitzer Model and other methods for modeling concentrated solutions.

- Built in database containing hundreds of model parameters and physicochemical properties for different ions.

- Customizable *modeling engine system* that allows the Solution API to work with multiple electrolyte models.

- *Units-aware calculations* (by means of the pint library)

CONTENTS:

4.1 Quickstart

pyEQL creates a new type (`Solution` class) to represent a chemical solution. It also comes pre-loaded with a database of diffusion coefficients, activity correction parameters, and other data on a variety of common electrolytes. Virtually all of the user-facing functions in `pyEQL` are accessed through the `Solution` class.

4.1.1 Creating a Solution Object

Create a Solution object by invoking the Solution class:

```
>>> import pyEQL
>>> s1 = pyEQL.Solution()
>>> s1
<pyEQL.pyEQL.Solution at 0x7f9d188309b0>
```

If no arguments are specified, `pyEQL` creates a 1-L solution of water at pH 7 and 25 degC.

More usefully, you can specify solutes and bulk properties:

```
>>> s2 = pyEQL.Solution({'Na+':'0.5 mol/kg', 'Cl-': '0.5 mol/kg'}, pH=8, temperature =
→'20 degC', volume='8 L')
```

See *Creating a Solution* for more details.

4.1.2 Retrieving Solution Properties

Bulk Solution Properties

pyEQL provides a variety of methods to calculate or look up bulk properties like temperature, ionic strength, conductivity, and density.

```
>>> s2.volume
8.071524653929277 liter
>>> s2.density
1.0182802742389558 kilogram/liter
>>> s2.conductivity
4.083570230022633 siemens/meter
>>> s2.ionic_strength
0.500000505903012 mole/kilogram
```

Individual Solute Properties

You can also retrieve properties for individual solutes (or the solvent, water)

```
>>> s2.get_amount('Na+','mol/L')
0.4946847550064916 mole/liter
>>> s2.get_activity_coefficient('Na+)
0.6838526233869155
>>> s2.get_activity('Na+')
0.3419263116934578
>>> s2.get_property('Na+','transport.diffusion_coefficient')
1.1206048116287536e-05 centimeter2/second
```

See *Getting Concentrations* for more details.

4.1.3 Units-Aware Calculations using pint

pyEQL uses pint to perform units-aware calculations. The pint library creates Quantity objects that contain both a magnitude and a unit.

```
>>> from pyEQL import ureg
>>> test_qty = pyEQL.ureg('1 kg/m**3')
1.0 kilogram/meter3
>>> test_qty.magnitude
1.0
```

Many `pyEQL` methods require physical quantities to be input as strings, then these methods return pint `Quantity` objects. A string quantity must contain both a magnitude and a unit (e.g. '0.5 mol/L'). In general, pint recognizes common abbreviations and SI prefixes. Compound units must follow Python math syntax (e.g. cm**2 not cm2).

See the *Converting Units* for more details.

4.2 Demo Notebook

pyEQL is an open-source `python` library for solution chemistry calculations and ion properties

Documentation

GitHub

4.2.1 Installation

```
>>> pip install pyEQL
```

4.2.2 Main feature: The `Solution` class

```
[1]: from pyEQL import Solution
```

```
/home/ryan/mambaforge/envs/pbx/code/pyEQL/src/pyEQL/__init__.py:52: FutureWarning:
↪unitdeprecator is deprecated
The pyEQL UnitRegistry has been renamed from unit to ureg. Change 'from pyEQL import unit
↪' to 'from pyEQL import ureg'!
  globals()["unit"] = unitdeprecator()
```

```
[2]: s1 = Solution({"Mg+2": "0.2 mol/L", "Cl-1": "0.4 mol/L"}, temperature='20 degC')
```

```
WARNING 2023-10-17 09:36:21,530 solution.py _get_property 2089 Partial molar volume for
↪species H[+1] not corrected for temperature
WARNING 2023-10-17 09:36:21,538 solution.py _get_property 2089 Partial molar volume for
↪species OH[-1] not corrected for temperature
WARNING 2023-10-17 09:36:21,788 solution.py _get_property 2089 Partial molar volume for
↪species Mg[+2] not corrected for temperature
WARNING 2023-10-17 09:36:21,818 activity_correction.py _debye_parameter_volume 231 Debye-
↪Huckel limiting slope for volume is approximate when T is not equal to 25 degC
```

Bulk Properties

```
[3]: s1.density
```

$[3]: 1.0138757383570756 \frac{kg}{l}$

```
[4]: s1.conductivity
```

```
WARNING 2023-10-17 09:36:21,869 solution.py viscosity_kinematic 599 Viscosity
↪coefficients for MgCl2 not found. Viscosity will be approximate.
WARNING 2023-10-17 09:36:21,906 solution.py viscosity_kinematic 599 Viscosity
↪coefficients for MgCl2 not found. Viscosity will be approximate.
WARNING 2023-10-17 09:36:21,944 solution.py viscosity_kinematic 599 Viscosity
↪coefficients for MgCl2 not found. Viscosity will be approximate.
WARNING 2023-10-17 09:36:21,970 engines.py get_activity_coefficient 314 Ionic strength
↪too high to estimate activity for species H[+1]. Specify parameters for Pitzer model.
↪Returning unit activity coefficient
WARNING 2023-10-17 09:36:21,985 solution.py viscosity_kinematic 599 Viscosity
↪coefficients for MgCl2 not found. Viscosity will be approximate.
WARNING 2023-10-17 09:36:22,008 engines.py get_activity_coefficient 314 Ionic strength
↪too high to estimate activity for species OH[-1]. Specify parameters for Pitzer model.
↪Returning unit activity coefficient
```

$[4]: 3.299995263108894 \frac{S}{m}$

```
[5]: s1.volume
```

[5]: `1 l`

[6]: `s1.pressure`

[6]: $1\,\mathrm{atm}$

[7]: `s1.temperature`

[7]: $293.15\,\mathrm{K}$

[8]: `s1.osmotic_pressure`

[8]: $1286752.4185332006\,\mathrm{Pa}$

Composition

[9]: `s1.components`

[9]: `{'H2O(aq)': 55.221652761186476, 'Cl[-1]': 0.4, 'Mg[+2]': 0.2, 'H[+1]': 1e-07, 'OH[-1]':`
`↪1e-07}`

[10]: `s1.solvent`

[10]: `'H2O(aq)'`

[11]: `s1.cations`

[11]: `{'Mg[+2]': 0.2, 'H[+1]': 1e-07}`

[12]: `s1.anions`

[12]: `{'Cl[-1]': 0.4, 'OH[-1]': 1e-07}`

[13]: `s1.neutrals`

[13]: `{'H2O(aq)': 55.221652761186476}`

Species Concentrations

[14]: `s1.get_amount('Mg+2', 'M')`

[14]: $0.20000000000000007\,\mathrm{M}$

[15]: `s1.get_amount('Cl-', '%')`

[15]: $1.3987118404647676\$$

[16]: `s1.get_amount('Mg+2', 'eq/L')`

[16]: $0.4\,\frac{\mathrm{mol}}{\mathrm{l}}$

[17]: `s1.get_amount('Mg+2', 'ug/kg')`

[17]: $4886244.60412788\,\frac{\mathrm{g}}{\mathrm{kg}}$

Transport

```
[18]: s1.get_transport_number('Na+')
```

```
[18]: 0.0$
```

```
[19]: s1.get_transport_number('Mg+2')
```

```
[19]: 0.4099879515632778$
```

```
[20]: s1.get_transport_number('Cl-')
```

```
[20]: 0.5900109897851136$
```

Speciation

```
[21]: s1.equilibrate()
```

```
[22]: s1.components
```

```
[22]: {'H2O(aq)': 55.238455538403954, 'Cl[-1]': 0.38323989957700755, 'Mg[+2]': 0.
      →18323990520853942, 'MgCl[+1]': 0.016760093825573405, 'H[+1]': 1.2403230417432767e-07,
      →'OH[-1]': 9.844314720800745e-08, 'HCl(aq)': 5.431780489909693e-09, 'MgOH[+1]': 7.
      →932661202804441e-15, 'O2(aq)': 3.1477649388058775e-26, 'HClO(aq)': 8.450946375546259e-
      →29, 'ClO[-1]': 3.367672345557701e-29, 'H2(aq)': 5.442728186726209e-35, 'ClO2[-1]': 0.0,
      → 'ClO3[-1]': 0.0, 'ClO4[-1]': 0.0, 'HClO2(aq)': 0.0}
```

Saving `Solution` to a file

```
[23]: from monty.serialization import dumpfn
      dumpfn(s1, 'test_solution.json')
```

```
[24]: s1.as_dict()
```

```
[24]: {'@module': 'pyEQL.solution',
       '@class': 'Solution',
       '@version': '0.6.0.post1.dev23+g090ac81',
       'solutes': {'H2O(aq)': '55.238455538403954 mol',
        'Cl[-1]': '0.38323989957700755 mol',
        'Mg[+2]': '0.18323990520853942 mol',
        'MgCl[+1]': '0.016760093825573405 mol',
        'H[+1]': '1.2403230417432767e-07 mol',
        'OH[-1]': '9.844314720800745e-08 mol',
        'HCl(aq)': '5.431780489909693e-09 mol',
        'MgOH[+1]': '7.932661202804441e-15 mol',
        'O2(aq)': '3.1477649388058775e-26 mol',
        'HClO(aq)': '8.450946375546259e-29 mol',
        'ClO[-1]': '3.367672345557701e-29 mol',
        'H2(aq)': '5.442728186726209e-35 mol',
        'ClO2[-1]': '0.0 mol',
        'ClO3[-1]': '0.0 mol',
        'ClO4[-1]': '0.0 mol',
```

```
  'HClO2(aq)': '0.0 mol'},
 'volume': '1 l',
 'temperature': '293.15 K',
 'pressure': '1 atm',
 'pH': 6.90646518824501,
 'pE': 8.5,
 'balance_charge': None,
 'solvent': 'H2O(aq)',
 'engine': 'native',
 'database': {'@module': 'maggma.stores.mongolike',
  '@class': 'JSONStore',
  '@version': '0.19.1.post1.dev1792+g0517496',
  'paths': ['/home/ryan/mambaforge/envs/pbx/code/pyEQL/src/pyEQL/database/pyeql_db.json
→'],
  'read_only': True,
  'serialization_option': None,
  'serialization_default': None,
  'key': 'formula'}}
```

4.2.3 Units-Aware Calculations

```
[25]: s1.volume.to('mL')
```

```
[25]: 1000.0000000000001 ml
```

```
[26]: s1.volume.to('gal')
```

```
[26]: 0.26417205235814856 gal
```

```
[27]: s1.osmotic_pressure.to('bar').magnitude
```

```
WARNING 2023-10-17 09:36:22,373 engines.py get_osmotic_coefficient 462 Cannot calculate␣
→osmotic coefficient because Pitzer parameters for salt HClO3 are not specified.␣
→Returning unit osmotic coefficient
WARNING 2023-10-17 09:36:22,384 engines.py get_osmotic_coefficient 462 Cannot calculate␣
→osmotic coefficient because Pitzer parameters for salt HClO2 are not specified.␣
→Returning unit osmotic coefficient
```

```
[27]: 12.630074635540739
```

4.2.4 Contribution Opportunities

Benchmarking - Compiling additional validation data for activity, conductivity, etc. - Quantifying error associated with different models - Refactoring unit tests suite to separate benchmarking

Documentation - Writing tutorials - Writing expanded docs - Cleaning up / updating docstrings

New Features - Better viscosity model - Expanded unit testing (increase test coverage to 90%) - Additional properties - Additional mixing rules / models for mixed electrolytes

Database - Expand database doverage to include additional species - More viscosity coefficients - Add 'sho' parameter - More diffusion coefficients

Software Engineering - Additional refactoring (e.g., `mypy` linting for robustness) - Bugfixes

4.3 Installing

4.3.1 Use a conda environment

We highly recommend installing python in an isolated environment using conda (or its speedier, backward-compatible successor, mamba). In particular, we recommend the miniforge or mambaforge distributions of Python, which are lightweight distributions of conda that automatically activate the `conda-forge` channel for up-to-date scientific packages.

Note: If you are on a Windows machine, we recommend you install the Windows Subsystem for Linux (WSL) and set up your conda environments inside the WSL environment.

After installing `conda` / `mamba`, follow their instructions to create an environment. The steps should be similar to the following:

1. Open your terminal (or "Anaconda prompt" or "Miniforge prompt" on Windows)

2. Pick a name for your environment (note: you can create many environments if you want)

3. type `conda create -n <name-you-picked> python=3.10` (if you install miniforge) or `mamba create -n <name-you-picked> python=3.10` (if you installed mambaforge) and press enter

4. After the environment is installed, type `conda activate <name-you-picked>` / `mamba activate <name-you-picked>` and press enter

4.3.2 pip install

Once Python is installed and your environment is activated you can install `pyEQL` from PyPi by typing the following command:

```
pip install pyEQL
```

This should automatically pull in the required *dependencies* as well.

Important: If you are NOT using a `conda` environment, may have to run 'pip3' rather than 'pip'. This will be the case if Python 2.x and Python 3.x are installed side-by-side on your system. You can tell if this is the case by typing the following command:

```
$ python --version
Python 2.7.12
```

This means Python 2.x is installed. If you run 'pip install' it will point to the Python 2.7 installation, but pyEQL only works on Python 3. So, try this:

```
$ python3 --version
Python 3.9.7
```

To get to Python 3.x, you have to type 'python3'. In this case, you would run 'pip3 install'

4.3.3 Other dependencies

pyEQL also requires the following packages:

- pint - for automated unit conversion
- pymatgen - used to interpret chemical formulas
- iapws - used to calculate the properties of water
- monty - used for saving and loading `Solution` objects to files
- maggma - used by the internal property database
- scipy
- numpy

If you use pip to install pyEQL (recommended), they should be installed automatically.

4.3.4 Installing the development branch

If you want to use the bleeding edge version before it is released to PyPi instead of the latest stable release, you can substitute the following for the above 'pip install' command:

```
pip install git+https://github.com/KingsburyLab/pyEQL.git@main
```

4.3.5 Manually install via Git

Simply navigate to a directory of your choice on your computer and clone the repository by executing the following terminal command:

```
git clone https://github.com/KingsburyLab/pyEQL
```

Then install by executing:

```
pip install -e pyEQL
```

Note: You may have to run 'pip3' rather than 'pip'. See the note in the *pip install* section.

4.4 Creating a `Solution`

The `Solution` class defines a pythonic interface for **creating**, **modifying**, and **estimating properties** of electrolyte solutions. It is the core feature of `pyEQL` and the primary user-facing class. There are several ways to create a `Solution`.

4.4.1 Empty solution

With no input arguments, you get an empty `Solution` at pH 7 and 1 atm pressure.

```
>>> from pyEQL import Solution
>>> s = Solution()
>>> print(s)
Volume: 1.000 l
Pressure: 1.000 atm
Temperature: 298.150 K
Components: ['H2O(aq)', 'H[+1]', 'OH[-1]']
```

4.4.2 Manual Creation

Typically, you will create a solution by specifying a list of solutes. Solutes are passed as a `dict` with amounts given **as strings** that include units (see *units*). Any unit that can be understood by `get_amount` is valid.

```
>>> from pyEQL import Solution
>>> s = Solution({"Na+": "0.5 mol/L", "Cl-": "0.5 mol/L"})
```

You can also specify conditions such as temperature, pressure, pH, and pE (redox potential).

Finally, you can manually create a solution with any list of solutes, temperature, pressure, etc. that you need:

```
>>> from pyEQL import Solution
>>> s1 = Solution(solutes={'Na+':'0.5 mol/kg', 'Cl-': '0.5 mol/kg'},
                  pH=8,
                  temperature = '20 degC',
                  volume='8 L',
                  pE = 4,
                  )
```

4.4.3 Using a preset

Alternatively, you can use the `pyEQL.functions.autogenerate()` function to easily create common solutions like seawater:

```
>>> from pyEQL.functions import autogenerate
>>> s2 = autogenerate('seawater')
<pyEQL.solution.Solution object at 0x7f057de6b0a0>
```

4.4.4 From a dictionary

If you have *converted a Solution to a dict*, you can re-instantiate it using the `Solution.from_dict()` class method.

4.4.5 From a file

If you *save a Solution to a .json file*, you can *recreate it* using monty.serialization.loadfn

```
>>> from monty.serialization import loadfn
>>> s = loadfn('test.json')
print(s)
Volume: 1.000 l
Pressure: 1.000 atm
Temperature: 298.150 K
Components: ['H2O(aq)', 'H[+1]', 'OH[-1]']
```

4.5 Writing Formulas

pyEQL interprets the chemical formula of a substance to calculate its molecular weight and formal charge. The formula is also used as a key to search the *property database* for parameters (e.g. diffusion coefficient) that are used in subsequent calculations.

4.5.1 How to Enter Valid Chemical Formulas

Generally speaking, type the chemical formula of your solute the "normal" way and pyEQL should be able to inerpret it. Internally, pyEQL uses a utility function pyEQL.utils.standardize_formula to process all formulas into a standard form. At present, this is done by passing the formula through the pymatgen.core.ion.Ion class. Anything that the Ion class can understand will be processed into a valid formula by pyEQL.

Here are some examples:

Substance	You enter	pyEQL understands
Sodium Chloride	"NaCl", "NaCl(aq)", or "ClNa"	"NaCl(aq)"
Sodium Sulfate	"Na(SO4)2" or "NaS2O8"	"Na(SO4)2(aq)"
Sodium Ion	"Na+", "Na+1", "Na1+", or "Na^{+}"	"Na[+1]"
Magnesium Ion	"Mg+2", "Mg++", or "Mg^{++}"	"Mg[+2]"
Methanol	"CH3OH", "CH4O"	"'CH3OH(aq)'"

Specifically, standardize_formula uses Ion.from_formula(<formula>).reduced_formla (shown in the right hand column of the table) to identify solutes. Notice that for charged species, the charges are always placed inside square brackets (e.g., Na[+1]) and always include the charge number (even for monovalent ions). Uncharged species are always suffixed by (aq) to disambiguate them from solids.

Important: **When writing multivalent ion formulas, it is strongly recommended that you put the charge number AFTER the + or - sign** (e.g., type "Mg+2" NOT "Mg2+"). The latter formula is ambiguous - it could mean Mg_2^+ or Mg^{+2} and it will be processed incorrectly into Mg[+0.5]

4.5.2 Manually testing a formula

If you want to make sure pyEQL is understanding your formula correctly, you can manually test it as follows:

```
>>> from pyEQL.utils import standardize_formula
>>> standardize_formula(<your_formula>)
...
```

4.5.3 Formulas you will see when using `Solution`

When using the `Solution` class,

- When creating a `Solution`, you can enter chemical formulas in any format you prefer, as long as `standardize_formula` can understand it (see *manual testing*).

- The keys (solute formulas) in `Solution.components` are standardized. So if you entered `Na+` for sodium ion, it will appear in `components` as `Na[+1]`.

- However, the `components` attribute is a special dictionary that automatically standardizes formulas when accessed. So, you can still enter the formula however you want. For example, the following all access or modify the same element in `components`:

```
>>> Solution.components.get('Na+')
>>> Solution.components["Na+1"]
>>> Solution.components.update("Na[+]": 2)
>>> Solution.components["Na[+1]"]
```

- Arguments to `Solution.get_property` can be entered in any format you prefer. When pyEQL queries the database, it will automatically standardize the formula.

- Property data in the database is uniquely identified by the standardized ion formula (output of `Ion.from_formula(<formula>).reduced_formla`, e.g. "Na[+1]" for sodium ion).

4.6 Converting Units

pyEQL uses pint to automatically interpret and convert units. For this reason, many quantitative arguments are passed to functions **as strings** rather than numbers. For example, to specify temperature, you pass `temperature='298 K'` and NOT `temperature=298`.

4.6.1 Quantity objects

Most `Solution` class methods return `pint` `Quantity` objects.

```
>>> from pyEQL import Solution
>>> s = Solution()
>>> s.pressure
<Quantity(1, 'standard_atmosphere')>
```

If you want to create a simple `Quantity` not attached to a `Solution`, you can do so as follows:

```
>>> from pyEQL import ureg
>>> q = ureg.Quantity('1 m')
```

`Quantity` objects have three important attributes: `magnitude`, `units`, and `dimensionality`. To get the numerical value, call magnitude

```
>>> from pyEQL import ureg
>>> q = ureg.Quantity('1 m')
>>> q.magnitude
1
```

Similarly, to get the units, call `units`

```
>>> from pyEQL import ureg
>>> q = ureg.Quantity('1 m')
>>> q.units
<Unit('meter')>
```

To convert from one unit to another, use `to()`:

```
>>> from pyEQL import ureg
>>> q = ureg.Quantity('1 m')
>>> q.to('ft')
<Quantity(3.2808399, 'foot')>
```

If you encounter a `DimensionalityError` when working with pyEQL, it probably means you are trying to do an operation on two quantities with incompatible units (or perhaps on a `Quantity` and a regular `float` or `int`). For example, you can't convert `m` into `m**3`:

```
>>> from pyEQL import ureg
>>> q = ureg.Quantity('1 m')
>>> q.to('m^3')
Traceback (most recent call last):
  File "<stdin>", line 1, in <module>
  File "/home/ryan/mambaforge/envs/pbx/lib/python3.10/site-packages/pint/facets/plain/
→quantity.py", line 517, in to
    magnitude = self._convert_magnitude_not_inplace(other, *contexts, **ctx_kwargs)
  File "/home/ryan/mambaforge/envs/pbx/lib/python3.10/site-packages/pint/facets/plain/
→quantity.py", line 462, in _convert_magnitude_not_inplace
    return self._REGISTRY.convert(self._magnitude, self._units, other)
  File "/home/ryan/mambaforge/envs/pbx/lib/python3.10/site-packages/pint/facets/plain/
→registry.py", line 961, in convert
    return self._convert(value, src, dst, inplace)
  File "/home/ryan/mambaforge/envs/pbx/lib/python3.10/site-packages/pint/facets/context/
→registry.py", line 403, in _convert
    return super()._convert(value, src, dst, inplace)
  File "/home/ryan/mambaforge/envs/pbx/lib/python3.10/site-packages/pint/facets/
→nonmultiplicative/registry.py", line 254, in _convert
    return super()._convert(value, src, dst, inplace)
  File "/home/ryan/mambaforge/envs/pbx/lib/python3.10/site-packages/pint/facets/plain/
→registry.py", line 1000, in _convert
    raise DimensionalityError(src, dst, src_dim, dst_dim)
pint.errors.DimensionalityError: Cannot convert from 'meter' ([length]) to 'meter ** 3'
→([length] ** 3)
```

Refer to the pint documentation for more etails about working with `Quantity`.

Note: Note that the meaning of `ureg` is equivalent in the above pyEQL examples and in the pint documentation. pyEQL instantiates its own `UnitRegistry` (with custom definitions for solution chemistry) and assigns it to the variable `ureg`. In most `pint` examples, the line `ureq = UnitRegistry()` does the same thing.

Important: if you use `pyEQL` in conjunction with another module that also uses pint for units-aware calculations, you must convert all `Quantity` objects to strings before passing them to the other module, as pint cannot perform mathematical operations on units that belong to different "registries." See the pint documentation for more details.

4.6.2 Custom Units

pyEQL extends the `pint` unit library to include some additional units that are commonly encountered in solution chemistry.

4.7 Getting Concentrations

4.7.1 Get the amount of a specific solute

To get the amount of a specific solute, use `get_amount()` and specify the units you want:

```
>>> from pyEQL import Solution
>>> s = Solution({"Mg+2": "0.5 mol/L", "Cl-": "1.0 mol/L"})
>>> s.get_amount('Mg[+2]', 'mol')
<Quantity(0.5, 'mole')>
```

`get_amount` is highly flexible with respect to the types of units it can interpret. You can request amounts in moles, mass, or equivalents (i.e., charge-weighted moles) per unit of mass or volume.

```
>>> s.get_amount('Mg[+2]', 'M')
<Quantity(0.5, 'molar')>
>>> s.get_amount('Mg[+2]', 'm')
<Quantity(0.506124103, 'mole / kilogram')>
>>> s.get_amount('Mg[+2]', 'eq/L')
<Quantity(1.0, 'mole / liter')>
>>> s.get_amount('Mg[+2]', 'ppm')
<Quantity(12152.5, 'milligram / liter')>
>>> s.get_amount('Mg[+2]', 'ppb')
<Quantity(12152500.0, 'microgram / liter')>
>>> s.get_amount('Mg[+2]', 'ppt')
<Quantity(1.21525e+10, 'nanogram / liter')>
```

Important: The unit `'ppt'` is ambiguous in the water community. To most researchers, it means "parts per trillion" or ng/L, while to many engineers and operators it means "parts per THOUSAND" or g/L. pyEQL interprets `ppt` as **parts per trillion**.

You can also request dimensionless concentrations as weight percent (`'%'`), mole fraction (`'fraction'`) or the total *number* of particles in the solution (`'count'`, useful for setting up simulation boxes).

```
>>> s.get_amount('Mg[+2]', '%')
<Quantity(1.17358141, 'dimensionless')>
>>> s.get_amount('Mg[+2]', 'fraction')
<Quantity(0.00887519616, 'dimensionless')>
>>> s.get_amount('Mg[+2]', 'count')
<Quantity(3.01107038e+23, 'dimensionless')>
```

4.7.2 See all components in the solution

You can inspect the solutes present in the solution via the `components` attribute. This comprises a dictionary of solute formula: moles, where 'moles' is the number of moles of that solute in the `Solution`. Note that the solvent (water) is present in `components`, too. `components` is reverse sorted, with the most predominant component (i.e., the solvent) listed first.

```
>>> from pyEQL import Solution
>>> s = Solution({"Mg+2": "0.5 mol/L", "Cl-": "1.0 mol/L"})
>>> s.components
{'H2O(aq)': 54.83678280993063, 'Cl[-1]': 1.0, 'Mg[+2]': 0.5, 'H[+1]': 1e-07, 'OH[-1]':
→1e-07}
```

Similarly, you can use the properties `anions`, `cations`, `neutrals`, and `solvent` to retrieve subsets of `components`:

```
>>> s.anions
{'Cl[-1]': 1.0, 'OH[-1]': 1e-07}
>>> s.cations
{'Mg[+2]': 0.5, 'H[+1]': 1e-07}
>>> s.neutrals
{'H2O(aq)': 54.83678280993063}
>>> s.solvent
'H2O(aq)'
```

Like `components`, all of the above dicts are sorted in order of decreasing amount.

4.7.3 Salt vs. Solute Concentrations

Sometimes the concentration of a dissolved *salt* (e.g., MgCl2) is of greater interest than the concentrations of the individual solutes (Mg+2 and Cl-). pyEQL has the ability to interpret a `Solution` composition and represent it as a mixture of salts.

To retrieve only *the predominant salt* (i.e., the salt with the highest concentration), use `get_salt`. This returns a `Salt` object with several useful attributes.

```
>>> from pyEQL import Solution
>>> s = Solution({"Mg+2": "0.4 mol/L", "Na+": "0.1 mol/L", "Cl-": "1.0 mol/L"})
>>> s.get_salt()
<pyEQL.salt_ion_match.Salt object at 0x7f0ded09fd30>
>>> s.get_salt().formula
'MgCl2'
>>> s.get_salt().anion
'Cl[-1]'
>>> s.get_salt().z_cation
```

```
2.0
>>> s.get_salt().nu_anion
2
```

To see a `dict` of all the salts in given solution, use `get_salt_dict()`. This method returns a dict keyed by the salt's formula, where the values are `Salt` objects converted into dictionaries. All the usual attributes like `anion`, `z_cation` etc. are accessible in the corresponding keys. Each value also contains a `mol` key giving the moles of the salt present.

```
>>> from pyEQL import Solution
>>> s = Solution({"Mg+2": "0.4 mol/L", "Na+": "0.1 mol/L", "Cl-": "1.0 mol/L"})
>>> s.get_salt_dict()
{'MgCl2': {'@module': 'pyEQL.salt_ion_match',
           '@class': 'Salt', '@version': '0.5.2',
           'cation': 'Mg[+2]',
           'anion': 'Cl[-1]',
           'mol': 0.4},
 'NaCl': {'@module': 'pyEQL.salt_ion_match',
          '@class': 'Salt', '@version': '0.5.2',
          'cation': 'Na[+1]',
          'anion': 'Cl[-1]',
          'mol': 0.1},
 'NaOH': {'@module': 'pyEQL.salt_ion_match',
          '@class': 'Salt', '@version': '0.5.2',
          'cation': 'Na[+1]',
          'anion': 'OH[-1]',
          'mol': 1e-07}
}
```

Refer to the *Salt Matching module reference* for more details.

4.7.4 Total Element Concentrations

"Total" concentrations (i.e., concentrations of all species containing a particular element) are important for certain types of equilibrium calculations. These can be retrieved via `get_total_amount`. `get_total_amount` takes an element name as the first argument, and a unit as the second.

```
>>> from pyEQL import Solution
>>> s = Solution({"Mg+2": "0.5 mol/L", "Cl-": "1.0 mol/L"})
>>> s.equilibrate()
>>> s.components
{'H2O(aq)': 54.85346847938828, 'Cl[-1]': 0.9186683796593457, 'Mg[+2]': 0.
→41866839204646417, 'MgCl[+1]': 0.08133160795194606, 'OH[-1]': 1.4679440802358093e-07,
→'H[+1]': 1.1833989847708719e-07, 'HCl(aq)': 1.2388705241250352e-08, 'MgOH[+1]': 3.
→9747494391744955e-13, 'O2(aq)': 7.027122927701743e-25, 'HClO(aq)': 1.5544872892067526e-
→27, 'ClO[-1]': 6.339364938003202e-28, 'H2(aq)': 5.792559717610837e-35, 'ClO2[-1]': 0.0,
→ 'ClO3[-1]': 0.0, 'ClO4[-1]': 0.0, 'HClO2(aq)': 0.0}
>>> s.get_total_amount('Mg', 'mol')
<Quantity(0.5, 'mole')>
```

4.7.5 Elements present in a `Solution`

If you just want to know the elements present in the `Solution`, use `elements`. This returns a list of elements, sorted alphabetically.

```
>>> from pyEQL import Solution
>>> s = Solution({"Mg+2": "0.5 mol/L", "Cl-": "1.0 mol/L"})
>>> s.elements
['Cl', 'H', 'Mg', 'O']
```

4.8 Arithmetic Operations

4.8.1 Addition and Subtraction

You can use the + operator to mix (combine) two solutions. The moles of each component in the two solutions will be added together, and the volume of the mixed solution will be *approximately* equal to the sum of the two volumes, depending on the electrolyte modeling engine used. The pressure and temperature of the mixed solution are computed as volume-weighted averages.

```
>>> from pyEQL import Solution
>>> s1 = Solution({"Na+": "0.5 mol/L", "Cl-": "0.5 mol/L"})
>>> s2 = Solution({"Na+": "0.1 mol/L", "Cl-": "0.1 mol/L"})
>>> s1+s2
<pyEQL.solution.Solution object at 0x7f171aee3af0>
>>> (s1+s2).get_amount('Na+', 'mol')
<Quantity(0.6, 'mole')>
>>> (s1+s2).volume
<Quantity(1.99989659, 'liter')>
```

Note: Both `Solution` involved in an addition operation must use the same *electrolyte modeling engine*.

Subtraction is not implemented and will raise a `NotImplementedError`.

```
>>> s1-s2
Traceback (most recent call last):
  File "<stdin>", line 1, in <module>
  File "/home/ryan/mambaforge/envs/pbx/code/pyEQL/src/pyEQL/solution.py", line 2481, in _
↪_sub__
    raise NotImplementedError("Subtraction of solutions is not implemented.")
NotImplementedError: Subtraction of solutions is not implemented.
```

4.8.2 Multiplication and Division

The * and / operators scale the volume and all component amounts by a factor.

```
from pyEQL import Solution
>>> s = Solution({"Na+": "0.2 mol/L", "Cl-": "0.2 mol/L"})
>>> s.volume
<Quantity(1, 'liter')>
>>> s.get_amount('Cl-', 'mol')
<Quantity(0.2, 'mole')>
>>> s*=1.5
<Quantity(1.5, 'liter')>
s.get_amount('Cl-', 'mol')
<Quantity(0.3, 'mole')>
```

The modulo operator // is not implemented.

4.9 Saving and Loading from Files

4.9.1 Serialization to `dict`

Any `Solution` can be converted into a `dict` by calling `as_dict`:

```
>>> from pyEQL import Solution
>>> s = Solution({"Na+": "0.5 mol/L", "Cl-": "0.5 mol/L"})
>>> s.as_dict()
{'@module': 'pyEQL.solution', '@class': 'Solution', '@version': '0.5.2', 'solutes': {
→'H2O(aq)': '55.34455402076251 mol', 'H[+1]': '1e-07 mol', 'OH[-1]': '1e-07 mol'},
→'volume': '1 l', 'temperature': '298.15 K', 'pressure': '1 atm', 'pH': 7.0, 'pE': 8.5,
→'balance_charge': None, 'solvent': 'H2O(aq)', 'engine': 'native', 'database': {'@module
→': 'maggma.stores.mongolike', '@class': 'JSONStore', '@version': '0.19.1.post1.
→dev1792+g0517496', 'paths': ['/home/ryan/mambaforge/envs/pbx/code/pyEQL/src/pyEQL/
→database/pyeql_db.json'], 'read_only': True, 'serialization_option': None,
→'serialization_default': None, 'key': 'formula'}}
```

This `dict` can be stored in a database or used to *recreate the Solution* using `from_dict()`.

4.9.2 Saving to a `.json` file

`Solution` can be serialized (and later recreated from) a `.json` file using `monty.serializtaion.dumpfn`.

```
>>> from pyEQL import Solution
>>> from monty.serialization import dumpfn
>>> s = Solution({"Na+": "0.5 mol/L", "Cl-": "0.5 mol/L"})
>>> dumpfn(s, 'test.json')
```

4.9.3 Loading from a `.json` file

Similarly, monty.serialization.loadfn can be used to create a `Solution` from a compatible `.json` file.

```
>>> from monty.serialization import loadfn
>>> s = loadfn('test.json')
print(s)
Volume: 1.000 l
Pressure: 1.000 atm
Temperature: 298.150 K
Components: ['H2O(aq)', 'H[+1]', 'OH[-1]']
```

Note: In a future release, `to_file()` / `from_file()` methods may be added to `Solution` to make the above steps easier. Please post on GitHub if you have strong opinions about this!

4.10 Electrolyte Modeling Engines

4.10.1 Overview

Every `Solution` is instantiated with an electrolyte modeling "engine", which is a subclass of *pyEQL.engine.EOS*. The modeling engine performs three functions:

1. Calculate species activity and osmotic coefficients via `get_activity_coefficient` and `get_osmotic_coefficient`, respectively

2. Update the composition of the `Solution` (i.e., speciation) via `equilibrate`

3. Calculate the volume occupied by the solutes via `get_solute_volume`

All other calculations are performed directly by the `Solution` class and are the same, regardless of the engine selected

The purpose of this architecture is to allow `Solution` to provide a **consistent interface** for working with electrolyte solutions, but allow the underlying models to be customized as needed to particular use cases.

pyEQL currently supports three modeling engines: `ideal`, `native`, and `phreeqc`, which are selected via the `engine` kwarg to `Solution.__init__()`. Each engine is briefly described below.

4.10.2 The `'native'` engine (Default)

The `native` engine is the default choice and was the only option available prior to version `0.6.0`.

Activity and osmotic coefficients

Activity coefficients are calculated using the "effetive Pitzer model" of Mistry et al. when possible. pyEQL selects parameters by identifying the predominant salt in the solution (see *Salt Matching*). The ionic strength is calculated based on all solutes, but only the predominant salt parameters are used in the Pitzer calculation.

If the required parameters are not available in the *property database*, the `native` engine decays gracefully through several models more appropriate for dilute solutions, including Davies, Guntelberg, and Debye-Huckel. See the *module reference* for full details.

Solute volumes

Solute volumes are also calculated according to the Pitzer model whenever parameters are available. Specifically, the apparent molar volume of the primary salt is calculated via Pitzer. The volumes of all other components (except the solvent, water) are added based on fixed partial molar volumes, if the data are available in the *property database*. If data are not available, the volume for that solute is not accounted for.

Speciation

Speciation calculations are provided by PHREEQC via `phreeqpython`. We use the `llnl.dat` PHREEQC database due to its applicability for moderate salinity water and the large number of species included (see Lu et al.). See `pyEQL.equilibrium.eqiulibrate_phreeqc` in the *module reference* for more details.

> **Warning:** Speciation support was added to the `native` engine in `v0.8.0` and should be considered experimental. Specifically, because the `native` engine uses a non-Pitzer PHREEQC database for speciation but uses the Pitzer model (when possible) for activity coefficients. As such, there may be subtle thermodynamic inconsistencies between the activities and the equilibrium concentrations returned by `equilibrate()`.

4.10.3 The `'phreeqc'` engine

The `phreeqc` engine uses `phreeqpython` for speciation, activity, and volume calculations. The PHREEQC engine uses the `phreeqc.dat` PHREEQC database by default, although it is possible to instantiate the engine with other databases such as `llnl.dat`, `pitzer.dat`, etc. See `pyEQL.equilibrium.eqiulibrate_phreeqc` in the *module reference* for more details.

Activity and osmotic coefficients

Activity coefficients are calculated by dividing the PHREEQC activity by the molal concentration of the solute.

Due to limitations in the `phreeqpython` interface, the osmotic coefficient is always returned as 1 at present.

> **Warning:** The `phreeqc` engine currently returns an osmotic coefficient of 1 and solute volume of 0 for all solutions. There appear to be limitations in the `phreeqpython` interface that make it difficult to access these properties.

Solute volumes

Due to limitations in the `phreeqpython` interface, solute volumes are ignored (as in the `ideal` engine). More research is needed to determine whether this is consistent with intended PHREEQC behavior (when using the default database) or not.

> **Warning:** The `phreeqc` engine currently returns an osmotic coefficient of 1 and solute volume of 0 for all solutions. There appear to be limitations in the `phreeqpython` interface that make it difficult to access these properties.

Speciation

Speciation calculations are provided by PHREEQC via `phreeqpython`.

4.10.4 The `'ideal'` engine

The `'ideal'` engine applies ideal solution behavior. Activity and osmotic coefficients are always equal to 1, solute volumes are always equal to zero, and there is no support for speciation.

4.10.5 Custom engines

The modeling engine system is designed to be extensible and customizable. To define a custom engine, you simply need to inherit from `pyEQL.engines.EOS` (or a pre-existing engine class) and then populate the abstract methods `get_activity_coefficient`), `get_osmotic_coefficient`, `get_solute_volume`, and `equilibrate`.

Equations that implement commonly used models or the above properties (such as the Debye-Huckel and Pitzer activity models, among others) are available in `pyEQL.activity_correction` and `pyEQL.equilibrium`, respectively. The idea is that end users can "compose" custom engine classes by mixing and matching the desired functions from these modules, adding custom logic as necessary.

4.11 Property Database

pyEQL is distributed with a database of solute properties and model parameters needed to perform its calculations. The database includes:

- Molecular weight, charge, and other chemical informatics information for any species
- Diffusion coefficients for 104 ions
- Pitzer model activity correction coefficients for 157 salts
- Pitzer model partial molar volume coefficients for 120 salts
- Jones-Dole "B" coefficients for 83 ions
- Hydrated and ionic radii for 23 ions
- Dielectric constant model parameters for 18 ions
- Partial molar volumes for 24 ions

pyEQL can automatically infer basic chemical informatics such as molecular weight and charge by passing a solute's formula to `pymatgen.core.ion.Ion` (See chemical formulas). For other physicochemical properties, it relies on data compiled into the included database. A list of the data and species covered is available *below*

4.11.1 Format

The database is distributed as a `.json` file containing serialized `Solute` objects that define the schema for aggregated property data (see *below*). By default, each instance of `Solution` loads this file as a `maggma JSONStore` and queries data from it using the `Store` interface.

If desired, users can point a `Solution` instance to an alternate database by using the `database` keyword argument at creation. The argument should contain either 1) the path to an alternate `.json` file (as a `str`) or 2) a `maggma.Store` instance. The data in the file or `Store` must match the schema defined by `Solute`, with the field `formula` used as the key field (unique identifier).

```
s1 = Solution(database='/path/to/my_database.json')
```

or

```
from maggma.core import JSONStore

db_store = JSONStore('/path/to/my_database.json', key='formula')
s1 = Solution(database=db_store)
```

4.11.2 The `Solute` class

`pyEQL.Solute` is a `dataclass` that defines a schema for organizing solute property data. You can think of the schema as a structured dictionary: `Solute` defines the naming and organization of the keys. You can create a basic `Solute` from just the solute's formula as follows:

```
>>> from pyEQL.solute import Solute
>>> Solute.from_formula('Ti+2')
Solute(formula='Ti[+2]', charge=2, molecular_weight='47.867 g/mol', elements=['Ti'],
→chemsys='Ti', pmg_ion=Ion: Ti1 +2, formula_html='Ti<sup>+2</sup>', formula_latex='Ti$^
→{+2}$', formula_hill='Ti', formula_pretty='Ti^+2', oxi_state_guesses=({'Ti': 2.0},), n_
→atoms=1, n_elements=1, size={'radius_ionic': None, 'radius_hydrated': None, 'radius_vdw
→': None, 'molar_volume': None}, thermo={'G_hydration': None, 'G_formation': None},
→transport={'diffusion_coefficient': None}, model_parameters={'activity_pitzer': {'Beta0
→': None, 'Beta1': None, 'Beta2': None, 'Cphi': None, 'Max_C': None}, 'molar_volume_
→pitzer': {'Beta0': None, 'Beta1': None, 'Beta2': None, 'Cphi': None, 'V_o': None, 'Max_
→C': None}, 'viscosity_jones_dole': {'B': None}})
```

This method uses `pymatgen` to populate the `Solute` with basic chemical information like molecular weight. You can access top-level keys in the schema via attribute, e.g.

```
>>> s.molecular_weight
'47.867 g/mol'
>>> s.charge
2.0
```

Other properties that are present in the schema, but not set, are `None`. For example, here we have not specified a diffusion coefficient. If we inspect the `transport` attribute, we see

```
>>> s.transport
{'diffusion_coefficient': None}
```

You can convert a `Solute` into a regular dictionary using `Solute.as_dict()`

```
>>> s.as_dict()
{'formula': 'Ti[+2]', 'charge': 2, 'molecular_weight': '47.867 g/mol', 'elements': ['Ti
↪'], 'chemsys': 'Ti', 'pmg_ion': Ion: Ti1 +2, 'formula_html': 'Ti<sup>+2</sup>',
↪'formula_latex': 'Ti$^{+2}$', 'formula_hill': 'Ti', 'formula_pretty': 'Ti^+2', 'oxi_
↪state_guesses': ({'Ti': 2.0},), 'n_atoms': 1, 'n_elements': 1, 'size': {'radius_ionic':
↪ None, 'radius_hydrated': None, 'radius_vdw': None, 'molar_volume': None}, 'thermo': {
↪'G_hydration': None, 'G_formation': None}, 'transport': {'diffusion_coefficient': None}
↪, 'model_parameters': {'activity_pitzer': {'Beta0': None, 'Beta1': None, 'Beta2': None,
↪ 'Cphi': None, 'Max_C': None}, 'molar_volume_pitzer': {'Beta0': None, 'Beta1': None,
↪'Beta2': None, 'Cphi': None, 'V_o': None, 'Max_C': None}, 'viscosity_jones_dole': {'B':
↪ None}}}
```

4.11.3 Searching the database

Once you have a created a `Solution`, it will automatically search the database for needed parameters whenever it needs to perform a calculation. For example, if you call `get_transport_number`, pyEQL will search the property database for diffusion coefficient data to use in the calculation. No user action is needed.

If you want to search the database yourself, or to inspect the values that pyEQL uses for a particular parameter, you can do so via the `get_property` method. First, create a `Solution`

```
>>> from pyEQL import Solution
>>> s1 = pyEQL.Solution
```

Next, call `get_property` with a solute name and the name of the property you need. Valid property names are any key in the `Solute` schema. Nested keys can be separated by periods, e.g. "model_parameters.activity_pitzer":

```
>>> s1.get_property('Mg+2', 'transport.diffusion_coefficient')
<Quantity(0.00705999997, 'centimeter ** 2 * liter * pascal * second / kilogram / meter
↪** 2')>
```

If the property exists, it will be returned as a `pint` `Quantity` object, which you can convert to specific units if needed, e.g.

```
>>> s1.get_property('Mg+2', 'transport.diffusion_coefficient').to('m**2/s')
<Quantity(7.05999997e-10, 'meter ** 2 / second')>
```

If the property does not exist in the database, `None` will be returned.

```
>>> s1.get_property('Mg+2', 'transport.randomproperty')
>>>
```

Although the database contains additional context about each and every property value, such as a citation, this information is not currently exposed via the `Solution` interface. Richer methods for exploring and adding to the database may be added in the future.

4.11.4 Species included

The database currently contains one or more physichochemical properties for each of the solutes listed below. More detailed information about which properties are available for which solutes may be added in the future.

- `Ac[+3]`
- `Ag(CN)2[-1]`
- `AgNO3(aq)`
- `Ag[+1]`
- `Ag[+2]`
- `Ag[+3]`
- `Al2(SO4)3(aq)`
- `Al[+3]`
- `AsO4[-3]`
- `Au(CN)2[-1]`
- `Au(CN)4[-1]`
- `Au[+1]`
- `Au[+2]`
- `Au[+3]`
- `B(H5C6)4[-1]`
- `B(OH)3(aq)`
- `B(OH)4[-1]`
- `BF4[-1]`
- `BO2[-1]`
- `Ba(ClO4)2(aq)`
- `Ba(NO3)2(aq)`
- `BaBr2(aq)`
- `BaC4O.3H2O(aq)`
- `BaCl2(aq)`
- `BaI2(aq)`
- `Ba[+2]`
- `BeSO4(aq)`
- `Be[+2]`
- `Bi[+3]`
- `BrO3[-1]`
- `Br[-0.33333333]`
- `Br[-1]`
- `C2N3[-1]`
- `CH3COO[-1]`
- `CNO[-1]`
- `CN[-1]`
- `CO3[-2]`
- `CSN[-1]`
- `CSeN[-1]`
- `Ca(ClO4)2(aq)`
- `Ca(NO3)2(aq)`
- `CaBr2(aq)`
- `CaCl2(aq)`
- `CaI2(aq)`
- `Ca[+2]`
- `Cd(ClO4)2(aq)`
- `Cd(NO2)2(aq)`
- `Cd(NO3)2(aq)`

(continues on next page)

- CdSO4(aq)
- Cd[+2]
- CeCl3(aq)
- Ce[+3]
- Ce[+4]
- ClO2[-1]
- ClO3[-1]
- ClO4[-1]
- Cl[-1]
- Co(CN)6[-3]
- Co(H3N)6[-3]
- Co(NO3)2(aq)
- CoBr2(aq)
- CoCl2(aq)
- CoI2(aq)
- Co[+2]
- Co[+3]
- Cr(NO3)3(aq)
- CrCl3(aq)
- CrO4[-2]
- Cr[+2]
- Cr[+3]
- Cs2SO4(aq)
- CsBr(aq)
- CsCl(aq)
- CsF(aq)
- CsHC2O.1H2O(aq)
- CsI(aq)
- CsNO2(aq)
- CsNO3(aq)
- CsOH(aq)
- Cs[+1]
- Cu(NO3)2(aq)
- CuCl2(aq)
- CuSO4(aq)
- Cu[+1]
- Cu[+2]
- Cu[+3]
- Dy[+2]
- Dy[+3]
- Er[+2]
- Er[+3]
- Eu(NO3)3(aq)
- EuCl3(aq)
- Eu[+2]
- Eu[+3]
- F[-1]
- Fe(CN)6[-3]
- Fe(CN)6[-4]
- FeCl2(aq)
- FeCl3(aq)
- Fe[+2]

- Fe[+3]
- Ga[+3]
- GdCl3(aq)
- Gd[+3]
- Ge[+2]
- H2CO3(aq)
- H2O(aq)
- H2SNO3[-1]
- H2SO4(aq)
- H3O[+1]
- H4BrN(aq)
- H4IN(aq)
- H4N2O3(aq)
- H4NCl(aq)
- H4NClO4(aq)
- H4N[+1]
- H4SNO4(aq)
- H5C6O7[-3]
- H5N2[+1]
- H8S(NO2)2(aq)
- HBr(aq)
- HCO2[-1]
- HCO3[-1]
- HCl(aq)
- HClO4(aq)
- HF2[-1]
- HI(aq)
- HNO3(aq)
- HO2[-1]
- HOsO5[-1]
- HSO3[-1]
- HSO4[-1]
- HS[-1]
- HSeO3[-1]
- H[+1]
- Hf[+4]
- Hg[+2]
- Ho[+2]
- Ho[+3]
- IO3[-1]
- IO4[-1]
- I[-1]
- In[+1]
- In[+2]
- In[+3]
- IrO4[-1]
- Ir[+3]
- K2CO3(aq)
- K2PHO4(aq)
- K2SO4(aq)
- K3Fe(CN)6(aq)
- K3PO4(aq)

- K4Fe(CN)6(aq)
- KBr(aq)
- KBrO3(aq)
- KCSN(aq)
- KCl(aq)
- KClO3(aq)
- KClO4(aq)
- KCrO4(aq)
- KF(aq)
- KHC2O.1H2O(aq)
- KHCO3(aq)
- KI(aq)
- KNO2(aq)
- KNO3(aq)
- KOH(aq)
- KPO3.1H2O(aq)
- K[+1]
- La(NO3)3(aq)
- LaCl3(aq)
- La[+3]
- Li2SO4(aq)
- LiBr(aq)
- LiCl(aq)
- LiClO4(aq)
- LiHC2O.1H2O(aq)
- LiI(aq)
- LiNO2(aq)
- LiNO3(aq)
- LiOH(aq)
- Li[+1]
- Lu[+3]
- Mg(ClO4)2(aq)
- Mg(NO3)2(aq)
- MgBr2(aq)
- MgC4O.3H2O(aq)
- MgCl2(aq)
- MgI2(aq)
- MgSO4(aq)
- Mg[+2]
- MnCl2(aq)
- MnO4[-1]
- MnSO4(aq)
- Mn[+2]
- Mn[+3]
- MoO4[-2]
- Mo[+3]
- NO2[-1]
- NO3[-1]
- N[-0.33333333]
- Na2CO3(aq)
- Na2PHO4(aq)
- Na2S2O3(aq)

- `Na2SO4(aq)`
- `Na3PO4(aq)`
- `NaBr(aq)`
- `NaBrO3(aq)`
- `NaCSN(aq)`
- `NaCl(aq)`
- `NaClO4(aq)`
- `NaCrO4(aq)`
- `NaF(aq)`
- `NaHC2O.1H2O(aq)`
- `NaHC3.2H2O(aq)`
- `NaHCO2(aq)`
- `NaHCO3(aq)`
- `NaI(aq)`
- `NaNO2(aq)`
- `NaNO3(aq)`
- `NaOH(aq)`
- `NaPO3.1H2O(aq)`
- `Na[+1]`
- `Nb[+3]`
- `Nd(NO3)3(aq)`
- `NdCl3(aq)`
- `Nd[+2]`
- `Nd[+3]`
- `Ni(NO3)2(aq)`
- `NiCl2(aq)`
- `NiSO4(aq)`
- `Ni[+2]`
- `Ni[+3]`
- `Np[+3]`
- `Np[+4]`
- `OH[-1]`
- `Os[+3]`
- `P(HO2)2[-1]`
- `P(OH)2[-1]`
- `P2O7[-4]`
- `P3O10[-5]`
- `PF6[-1]`
- `PH9(NO2)2(aq)`
- `PHO4[-2]`
- `PO3F[-2]`
- `PO3[-1]`
- `PO4[-3]`
- `Pa[+3]`
- `Pb(ClO4)2(aq)`
- `Pb(NO3)2(aq)`
- `Pb[+2]`
- `Pd[+2]`
- `Pm[+2]`
- `Pm[+3]`
- `Po[+2]`
- `PrCl3(aq)`

```
– Pr[+2]
– Pr[+3]
– Pt[+2]
– Pu[+2]
– Pu[+4]
– Ra[+2]
– Rb2SO4(aq)
– RbBr(aq)
– RbCl(aq)
– RbF(aq)
– RbHC2O.1H2O(aq)
– RbI(aq)
– RbNO2(aq)
– RbNO3(aq)
– RbOH(aq)
– Rb[+1]
– ReO4[-1]
– Re[+1]
– Re[+3]
– Re[-1]
– Rh[+3]
– Ru[+2]
– Ru[+3]
– S2O3[-2]
– SO2[-1]
– SO3[-1]
– SO3[-2]
– SO4[-1]
– SO4[-2]
– S[-2]
– Sb(HO2)2[-1]
– Sb(OH)6[-1]
– ScCl3(aq)
– Sc[+2]
– Sc[+3]
– SeO3[-1]
– SeO4[-1]
– SeO4[-2]
– SiF6[-2]
– SmCl3(aq)
– Sm[+2]
– Sm[+3]
– Sn[+2]
– Sn[+4]
– Sr(ClO4)2(aq)
– Sr(NO3)2(aq)
– SrBr2(aq)
– SrCl2(aq)
– SrI2(aq)
– Sr[+2]
– Ta[+3]
– Tb[+3]
```

Chapter 4. Contents:

- TcO4[-1]
- Tc[+2]
- Tc[+3]
- Th(NO3)4(aq)
- Th[+4]
- Ti[+2]
- Ti[+3]
- Tl(ClO4)3(aq)
- Tl(NO2)3(aq)
- Tl(NO3)3(aq)
- TlH(C3O)2.4H2O(aq)
- Tl[+1]
- Tl[+3]
- Tm[+2]
- Tm[+3]
- U(ClO)2(aq)
- U(ClO5)2(aq)
- U(NO4)2(aq)
- UO2[+1]
- UO2[+2]
- USO6(aq)
- U[+3]
- U[+4]
- VO2[+1]
- V[+2]
- V[+3]
- WO4[-1]
- WO4[-2]
- W[+3]
- YCl3(aq)
- YNO3(aq)
- Y[+3]
- Yb[+2]
- Yb[+3]
- Zn(ClO4)2(aq)
- Zn(NO3)2(aq)
- ZnBr2(aq)
- ZnCl2(aq)
- ZnI2(aq)
- ZnSO4(aq)
- Zn[+2]
- Zr[+4]

4.12 Mixing Functions

pyEQL contains several mixing and equilibration functions that take `Solution` as arguments. pyEQL functions that take Solution objects as inputs or return Solution objects.

copyright
>   2013-2023 by Ryan S. Kingsbury

license
>   LGPL, see LICENSE for more details.

pyEQL.functions.**gibbs_mix**(*Solution1*, *Solution2*)

>   Return the Gibbs energy change associated with mixing two solutions.
>
>   **Parameters**
>
>   - **Solution1** (*Solution objects*) – The two solutions to be mixed.
>
>   - **Solution2** (*Solution objects*) – The two solutions to be mixed.
>
>   **Returns**
>   >   The change in Gibbs energy associated with complete mixing of the Solutions, in Joules.
>
>   **Return type**
>   >   Quantity

Notes

The Gibbs energy of mixing is calculated as follows

$$
Delta_{mix}G = \\
sum_i(n_c + n_d)RT \\
lna_b- \\
sum_i n_c RT \\
lna_c- \\
sum_i n_d RT \\
lna_d
$$

Where n is the number of moles of substance, T is the temperature in kelvin, and subscripts b, c, and d refer to the concentrated, dilute, and blended Solutions, respectively.

Note that dissociated ions must be counted as separate components, so a simple salt dissolved in water is a three component solution (cation, anion, and water).

References

Koga, Yoshikata, 2007. *Solution Thermodynamics and its Application to Aqueous Solutions:
>   A differential approach.* Elsevier, 2007, pp. 23-37.

pyEQL.functions.**entropy_mix**(*Solution1*, *Solution2*)

>   Return the ideal mixing entropy associated with mixing two solutions.
>
>   **Parameters**
>
>   - **Solution1** (*Solution objects*) – The two solutions to be mixed.

- **Solution2** (`Solution objects`) – The two solutions to be mixed.

Returns

The ideal mixing entropy associated with complete mixing of the Solutions, in Joules.

Return type

Quantity

Notes

The ideal entropy of mixing is calculated as follows

$$Delta_{mix}S = \\ sum_i(n_c + n_d)RT \\ lnx_b- \\ sum_i n_c RT \\ lnx_c- \\ sum_i n_d RT \\ lnx_d$$

Where n is the number of moles of substance, T is the temperature in kelvin, and subscripts b, c, and d refer to the concentrated, dilute, and blended Solutions, respectively.

Note that dissociated ions must be counted as separate components, so a simple salt dissolved in water is a three component solution (cation, anion, and water).

References

Koga, Yoshikata, 2007. *Solution Thermodynamics and its Application to Aqueous Solutions:

A differential approach.* Elsevier, 2007, pp. 23-37.

pyEQL.functions.**donnan_eql**(*solution*, *fixed_charge*)

Return a solution object in equilibrium with fixed_charge.

Parameters

- **solution** (`Solution object`) – The external solution to be brought into equilibrium with the fixed charges

- **fixed_charge** (`str quantity`) – String representing the concentration of fixed charges, including sign. May be specified in mol/L or mol/kg units. e.g. '1 mol/kg'

Returns

A solution that has established Donnan equilibrium with the external (input) Solution

Return type

Solution

Notes

The general equation representing the equilibrium between an external electrolyte solution and an ion-exchange medium containing fixed charges is

In addition, electroneutrality must prevail within the membrane phase:

$$\bar{C}_+ z_+ + \bar{X} + \bar{C}_- z_- = 0$$

Where C represents concentration and X is the fixed charge concentration in the membrane or ion exchange phase.

This function solves these two equations simultaneously to arrive at the concentrations of the cation and anion in the membrane phase. It returns a solution equal to the input solution except that the concentrations of the predominant cation and anion have been adjusted according to this equilibrium.

NOTE that this treatment is only capable of equilibrating a single salt. This salt is identified by the get_salt() method.

References

Strathmann, Heiner, ed. *Membrane Science and Technology* vol. 9, 2004. Chapter 2, p. 51.
http://dx.doi.org/10.1016/S0927-5193(04)80033-0

4.12.1 See Also:

get_salt()

pyEQL.functions.**autogenerate**(*solution: Literal['seawater', 'rainwater', 'wastewater', 'urine', 'Ringers lactate', 'normal saline']*)

This method provides a quick way to create Solution objects representing commonly-encountered solutions, such as seawater, rainwater, and wastewater.

> **Parameters**
>> **solution** (`str`) – String representing the desired solution Valid entries are 'seawater', 'rainwater', 'wastewater',and 'urine'
>
> **Returns**
>> A pyEQL Solution object.
>
> **Return type**
>> Solution

Notes

The following sections explain the different solution options:

- '' - empty solution, equivalent to pyEQL.Solution()
- 'rainwater' - pure water in equilibrium with atmospheric CO2 at pH 6
- 'seawater' or 'SW'- Standard Seawater. See Table 4 of the Reference for Composition [1]_
- 'wastewater' or 'WW' - medium strength domestic wastewater. See Table 3-18 of [2]_
- 'urine' - typical human urine. See Table 3-15 of [2]_
- 'normal saline' or 'NS' - normal saline solution used in medicine [3]_
- 'Ringers lacatate' or 'RL' - Ringer's lactate solution used in medicine [4]_

4.12.2 References:

4.13 `Solution` Class Reference

This page contains detailed information on each of the methods, attributes, and properties in `Solution`. Use the sidebar on the right for easier navigation.

4.13.1 Solution

class pyEQL.**Solution**(*solutes: list[list[str]] | dict[str, str] | None = None, volume: str | None = None, temperature: str = '298.15 K', pressure: str = '1 atm', pH: float = 7, pE: float = 8.5, balance_charge: str | None = None, solvent: str | list = 'H2O', engine: EOS | Literal['native', 'ideal', 'phreeqc'] = 'native', database: str | Path | Store | None = None*)

Class representing the properties of a solution. Instances of this class contain information about the solutes, solvent, and bulk properties.

__init__(*solutes: list[list[str]] | dict[str, str] | None = None, volume: str | None = None, temperature: str = '298.15 K', pressure: str = '1 atm', pH: float = 7, pE: float = 8.5, balance_charge: str | None = None, solvent: str | list = 'H2O', engine: EOS | Literal['native', 'ideal', 'phreeqc'] = 'native', database: str | Path | Store | None = None*)

> **Parameters**
>
> - **solutes** – dict, optional. Keys must be the chemical formula, while values must be str Quantity representing the amount. For example:
>
>   {"Na+": "0.1 mol/L", "Cl-": "0.1 mol/L"}
>
>   Note that an older "list of lists" syntax is also supported; however this will be deprecated in the future and is no longer recommended. The equivalent list syntax for the above example is
>
>   [["Na+", "0.1 mol/L"], ["Cl-", "0.1 mol/L"]]
>
>   Defaults to empty (pure solvent) if omitted
>
> - **volume** – str, optional Volume of the solvent, including the unit. Defaults to '1 L' if omitted. Note that the total solution volume will be computed using partial molar volumes of the respective solutes as they are added to the solution.
>
> - **temperature** – str, optional The solution temperature, including the ureg. Defaults to '25 degC' if omitted.
>
> - **pressure** – Quantity, optional The ambient pressure of the solution, including the unit. Defaults to '1 atm' if omitted.
>
> - **pH** – number, optional Negative log of H+ activity. If omitted, the solution will be initialized to pH 7 (neutral) with appropriate quantities of H+ and OH- ions
>
> - **pe** – the pE value (redox potential) of the solution. Lower values = more reducing, higher values = more oxidizing. At pH 7, water is stable between approximately -7 to +14. The default value corresponds to a pE value typical of natural waters in equilibrium with the atmosphere.

- **balance_charge** – The strategy for balancing charge during init and equilibrium calculations. Valid options are 'pH', which will adjust the solution pH to balance charge, 'pE' which will adjust the redox equilibrium to balance charge, or the name of a dissolved species e.g. 'Ca+2' or 'Cl-' that will be added/subtracted to balance charge. If set to None, no charge balancing will be performed either on init or when equilibrate() is called.

- **solvent** – Formula of the solvent. Solvents other than water are not supported at this time.

- **engine** – Electrolyte modeling engine to use. See documentation for details on the available engines.

- **database** – path to a .json file (str or Path) or maggma Store instance that contains serialized SoluteDocs. *None* (default) will use the built-in pyEQL database.

Examples

```
>>> s1 = pyEQL.Solution({'Na+': '1 mol/L','Cl-': '1 mol/L'},temperature='20 degC
→',volume='500 mL')
>>> print(s1)
Components:
Volume: 0.500 l
Pressure: 1.000 atm
Temperature: 293.150 K
Components: ['H2O(aq)', 'H[+1]', 'OH[-1]', 'Na[+1]', 'Cl[-1]']
```

property mass: Quantity

Return the total mass of the solution.

The mass is calculated each time this method is called. :param None: :param Returns: :param ———-: :param Quantity: :type Quantity: the mass of the solution, in kg

property solvent_mass: Quantity

Return the mass of the solvent.

This property is used whenever mol/kg (or similar) concentrations are requested by get_amount()

> **Returns**
>
> The mass of the solvent, in kg

See Also:

get_amount()

property volume: Quantity

Return the volume of the solution.

Returns:

Quantity: the volume of the solution, in L

property temperature: Quantity

Return the temperature of the solution in Kelvin.

property pressure: Quantity

Return the hydrostatic pressure of the solution in atm.

property pH: float | None

Return the pH of the solution.

p(*solute: str*, *activity=True*) → float | None

Return the negative log of the activity of solute.

Generally used for expressing concentration of hydrogen ions (pH)

Parameters

- **solute** (*str*) – String representing the formula of the solute

- **activity** (*bool, optional*) – If False, the function will use the molar concentration rather than the activity to calculate p. Defaults to True.

- **Returns** –

- **------- –**

- **Quantity** – The negative log10 of the activity (or molar concentration if activity = False) of the solute.

property density: Quantity

Return the density of the solution.

Density is calculated from the mass and volume each time this method is called.

Returns:

Quantity: The density of the solution.

property dielectric_constant: Quantity

Returns the dielectric constant of the solution.

Parameters

- **None** –

- **Returns** –

- **------- –**

- **Quantity** (*the dielectric constant of the solution, dimensionless.*) –

- **Notes** –

- **----- –**

- **al.** (*Implements the following equation as given by Zuber et*) –

- **math:** (*..*) – epsilon = epsilon_{solvent} over 1 + sum_i alpha_i x_i:

:param where α_i is a coefficient specific to the solvent and ion: :param and x_i: :param is the mole fraction of the ion in solution.:

References:

.A. Zuber, L. Cardozo-Filho, V.F. Cabral, R.F. Checoni, M. Castier, An empirical equation for the dielectric constant in aqueous and nonaqueous electrolyte mixtures, Fluid Phase Equilib. 376 (2014) 116-123. doi:10.1016/j.fluid.2014.05.037.

property chemical_system: str

Return the chemical system of the Solution as a "-" separated list of elements, sorted alphabetically. For example, a solution containing CaCO3 would have a chemical system of "C-Ca-H-O".

property elements: list

Return a list of elements that are present in the solution. For example, a solution containing CaCO3 would return ["C", "Ca", "H", "O"]

property cations: dict[str, float]

moles} that are cations. The returned dict is sorted by amount in descending order.

> **Type**
>
> > Returns the subset of *components* {formula

property anions: dict[str, float]

moles} that are anions. The returned dict is sorted by amount in descending order.

> **Type**
>
> > Returns the subset of *components* {formula

property neutrals: dict[str, float]

moles} that are neutral (not charged). The returned dict is sorted by amount in descending order.

> **Type**
>
> > Returns the subset of *components* {formula

property viscosity_dynamic: Quantity

Return the dynamic (absolute) viscosity of the solution.

Calculated from the kinematic viscosity

See Also:

viscosity_kinematic

property viscosity_kinematic: Quantity

Return the kinematic viscosity of the solution.

Notes:

The calculation is based on a model derived from the Eyring equation and presented in

$$\ln \nu = \ln \frac{\nu_w MW_w}{\sum_i x_i MW_i} + 15x_+^2 + x_+^3 \delta G_{123}^* + 3x_+ \delta G_{23}^* (1 - 0.05x_+)$$

Where:

$$\delta G_{123}^* = a_o + a_1 (T)^{0.75}$$

$$\delta G_{23}^* = b_o + b_1 (T)^{0.5}$$

In which ν is the kinematic viscosity, MW is the molecular weight, x_+ is the mole fraction of cations, and T is the temperature in degrees C.

The a and b fitting parameters for a variety of common salts are included in the database.

References:

Vásquez-Castillo, G.; Iglesias-Silva, G. a.; Hall, K. R. An extension of the McAllister model to correlate kinematic viscosity of electrolyte solutions. Fluid Phase Equilib. 2013, 358, 44-49.

See Also:

viscosity_dynamic()

property conductivity: Quantity

Compute the electrical conductivity of the solution.

> **Parameters**
>
> > - **None** –
> >
> > - **Returns** –
> >
> > - **-------** –
> >
> > - **Quantity** – The electrical conductivity of the solution in Siemens / meter.
> >
> > - **Notes** –
> >
> > - **-----** –
> >
> > - **respective** *(Conductivity is calculated by summing the molar conductivities of the)* –
> >
> > - **solutes** –
> >
> > - **exponent.** *(but they are activity-corrected and adjusted using an empricial)* –
> >
> > - **hc** *(This approach is used in PHREEQC and Aqion models aq)* –
> >
> > - **math::** *(..)* – EC = {F^2 over R T} sum_i D_i z_i ^ 2 gamma_i ^ {alpha} m_i
> >
> > - **Where** –
> >
> > - **math::** – alpha = begin{cases}
> >
> >   > {frac{0.6}{sqrt{| z_{i} | }}} & {I < 0.36 | z_{i} | } {frac{sqrt{I}}{| z_i |}} & otherwise
> >
> >   end{cases}
> >
> > - **Note** *(PHREEQC uses the molal rather than molar concentration according to)* –
> >
> > - **http** *(.. [hc])* –
> >
> > - **References** –
> >
> > - **----------** –
> >
> > - **https** *(.. [aq])* –
> >
> > - **http** –

- **Also** (*See*) –

- -------- –

:param   *ionic_strength*:   :param   get_molar_conductivity():   :param
get_activity_coefficient():

property ionic_strength: Quantity

Return the ionic strength of the solution.

Return the ionic strength of the solution, calculated as 1/2 * sum (molality * charge ^2) over all the ions.

Molal (mol/kg) scale concentrations are used for compatibility with the activity correction formulas.

Returns:

Quantity :
The ionic strength of the parent solution, mol/kg.

See Also:

get_activity() *get_water_activity()*

Notes:

The ionic strength is calculated according to:

$$I = \sum_i m_i z_i^2$$

Where m_i is the molal concentration and z_i is the charge on species i.

Examples:

```
>>> s1 = pyEQL.Solution([['Na+','0.2 mol/kg'],['Cl-','0.2 mol/kg']])
>>> s1.ionic_strength
<Quantity(0.20000010029672785, 'mole / kilogram')>
```

```
>>> s1 = pyEQL.Solution([['Mg+2','0.3 mol/kg'],['Na+','0.1 mol/kg'],['Cl-','0.7↵
↪mol/kg']],temperature='30 degC')
>>> s1.ionic_strength
<Quantity(1.0000001004383303, 'mole / kilogram')>
```

property charge_balance: float

Return the charge balance of the solution.

Return the charge balance of the solution. The charge balance represents the net electric charge on the solution and SHOULD equal zero at all times, but due to numerical errors will usually have a small nonzero value. It is calculated according to:

$$CB = \sum_i n_i z_i$$

where n_i is the number of moles, and z_i is the charge on species i.

Returns:

float :
> The charge balance of the solution, in equivalents (mol of charge) per L.

property alkalinity: Quantity
> Return the alkalinity or acid neutralizing capacity of a solution.

Returns:

Quantity :
> The alkalinity of the solution in mg/L as CaCO3

Notes:

The alkalinity is calculated according to [stm]

$$Alk = \sum_i z_i C_B + \sum_i z_i C_A$$

Where C_B and C_A are conservative cations and anions, respectively (i.e. ions that do not participate in acid-base reactions), and z_i is their signed charge. In this method, the set of conservative cations is all Group I and Group II cations, and the conservative anions are all the anions of strong acids.

References:

property hardness: Quantity
> Return the hardness of a solution.
>
> Hardness is defined as the sum of the equivalent concentrations of multivalent cations as calcium carbonate.
>
> NOTE: at present pyEQL cannot distinguish between mg/L as CaCO3 and mg/L units. Use with caution.

> **Parameters**
>> • **None** –
>>
>> • **Returns** –
>>
>> • **-------** –
>>
>> • **Quantity** – The hardness of the solution in mg/L as CaCO3

property total_dissolved_solids: Quantity
> Total dissolved solids in mg/L (equivalent to ppm) including both charged and uncharged species.
>
> The TDS is defined as the sum of the concentrations of all aqueous solutes (not including the solvent), except for H[+1] and OH[-1]].

property TDS: Quantity
> Alias of *total_dissolved_solids()*

property debye_length: Quantity

Return the Debye length of a solution.

Debye length is calculated as [wk3]

$$\kappa^{-1} = \sqrt{\left(\frac{\epsilon_r \epsilon_o k_B T}{(2 N_A e^2 I)}\right)}$$

where I is the ionic strength, ϵ_r and ϵ_r are the relative permittivity and vacuum permittivity, k_B is the Boltzmann constant, and T is the temperature, e is the elementary charge, and N_A is Avogadro's number.

Returns The Debye length, in nanometers.

References: .. [wk3] https://en.wikipedia.org/wiki/Debye_length#Debye_length_in_an_electrolyte

See also:

ionic_strength dielectric_constant

property bjerrum_length: Quantity

Return the Bjerrum length of a solution.

Bjerrum length represents the distance at which electrostatic interactions between particles become comparable in magnitude to the thermal energy.:math:*lambda_B* is calculated as

$$\lambda_B = \frac{e^2}{(4\pi\epsilon_r \epsilon_o k_B T)}$$

where e is the fundamental charge, ϵ_r and ϵ_r are the relative permittivity and vacuum permittivity, k_B is the Boltzmann constant, and T is the temperature.

> **Parameters**
>
> - **None** –
> - **Returns** –
> - **-------** –
> - **Quantity** – The Bjerrum length, in nanometers.
> - **References** –
> - **----------** –
> - **https** (*//en.wikipedia.org/wiki/Bjerrum_length*) –
> - **Examples** –
> - **--------** –
> - **pyEQL.Solution()** (*>>> s1 =*) –
> - **s1.bjerrum_length** (*>>>*) –
> - **<Quantity(0.7152793009386953** –
> - **'nanometer')>** –
> - **Also** (*See*) –
> - **--------** –

:param *dielectric_constant*:

property osmotic_pressure: Quantity

Return the osmotic pressure of the solution relative to pure water.

> **Returns**
>> The osmotic pressure of the solution relative to pure water in Pa

See also:

get_water_activity get_osmotic_coefficient get_salt

Notes

Osmotic pressure is calculated based on the water activity [sata] [wk]

$$\Pi = -\frac{RT}{V_w} \ln a_w$$

Where Π is the osmotic pressure, V_w is the partial molar volume of water (18.2 cm**3/mol), and a_w is the water activity.

References

Examples

```
>>> s1=pyEQL.Solution()
>>> s1.osmotic_pressure
<Quantity(0.495791416, 'pascal')>
```

```
>>> s1 = pyEQL.Solution([['Na+','0.2 mol/kg'],['Cl-','0.2 mol/kg']])
>>> soln.osmotic_pressure
<Quantity(906516.7318131207, 'pascal')>
```

get_amount(*solute: str*, *units: str = 'mol/L'*) → Quantity

Return the amount of 'solute' in the parent solution.

The amount of a solute can be given in a variety of unit types. 1. substance per volume (e.g., 'mol/L', 'M') 2. equivalents (i.e., moles of charge) per volume (e.g., 'eq/L', 'meq/L') 3. substance per mass of solvent (e.g., 'mol/kg', 'm') 4. mass of substance (e.g., 'kg') 5. moles of substance ('mol') 6. mole fraction ('fraction') 7. percent by weight (%) 8. number of molecules ('count') 9. "parts-per-x" units, where ppm = mg/L, ppb = ug/L ppt = ng/L

> **Parameters**
>> - **solute** (str) – String representing the name of the solute of interest
>>
>> - **units** (in the specified) – Units desired for the output. Examples of valid units are 'mol/L','mol/kg','mol', 'kg', and 'g/L' Use 'fraction' to return the mole fraction. Use '%' to return the mass percent
>>
>> - **Returns** –
>>
>> - **-------** –
>>
>> - **question** (The amount of the solute in) –
>>
>> - **units** –

See Also:

add_amount   set_amount   get_total_amount   get_osmolarity   get_osmolality   get_mass
get_total_moles_solute

get_components_by_element() → dict[str, list]

Return a list of all species associated with a given element. Elements (keys) are suffixed with their oxidation state in parentheses, e.g.,

{"Na(1)":["Na[+1]", "NaOH(aq)"]}

Species associated with each element are sorted in descending order of the amount present (i.e., the first species listed is the most abundant).

get_el_amt_dict()

Return a dict of Element: amount in mol

Elements (keys) are suffixed with their oxidation state in parentheses, e.g. "Fe(2)", "Cl(-1)".

get_total_amount(*element: str*, *units*) → Quantity

Return the total amount of 'element' (across all solutes) in the solution.

> **Parameters**
> **element** – The symbol of the element of interest. The symbol can optionally be followed by the oxidation state in parentheses, e.g., "Na(1)", "Fe(2)", or "O(0)". If no oxidation state is given, the total concentration of the element (over all oxidation states) is returned.

> **units**
> [str] Units desired for the output. Examples of valid units are 'mol/L','mol/kg','mol', 'kg', and 'g/L'

> **Returns:**

> The total amount of the element in the solution, in the specified units

> **See also:**

> *get_amount*

add_solute(*formula: str*, *amount: str*)

Primary method for adding substances to a pyEQL solution.

> **Parameters**
> - **formula** (*str*) – Chemical formula for the solute. Charged species must contain a + or - and (for polyvalent solutes) a number representing the net charge (e.g. 'SO4-2').
> - **amount** (*str*) – The amount of substance in the specified unit system. The string should contain both a quantity and a pint-compatible representation of a ureg. e.g. '5 mol/kg' or '0.1 g/L'

add_solvent(*formula: str*, *amount: str*)

Same as add_solute but omits the need to pass solvent mass to pint.

add_amount(*solute: str*, *amount: str*)

Add the amount of 'solute' to the parent solution.

> **Parameters**
> - **solute** (*str*) – String representing the name of the solute of interest

- **amount** (`str quantity`) – String representing the concentration desired, e.g. '1 mol/kg' If the units are given on a per-volume basis, the solution volume is not recalculated If the units are given on a mass, substance, per-mass, or per-substance basis, then the solution volume is recalculated based on the new composition

- **Returns** –

- **-------** –

- **modified.** (`Nothing. The concentration of solute is`) –

set_amount(*solute: str*, *amount: str*)

> Set the amount of 'solute' in the parent solution.
>
> > **Parameters**
> >
> > - **solute** (`str`) – String representing the name of the solute of interest
> >
> > - **amount** (`str Quantity`) – String representing the concentration desired, e.g. '1 mol/kg' If the units are given on a per-volume basis, the solution volume is not recalculated and the molar concentrations of other components in the solution are not altered, while the molal concentrations are modified.
> >
> >   If the units are given on a mass, substance, per-mass, or per-substance basis, then the solution volume is recalculated based on the new composition and the molal concentrations of other components are not altered, while the molar concentrations are modified.
> >
> > - **Returns** –
> >
> > - **-------** –
> >
> > - **modified.** (`Nothing. The concentration of solute is`) –

get_total_moles_solute() → Quantity

> Return the total moles of all solute in the solution.

get_moles_solvent() → Quantity

> Return the moles of solvent present in the solution.
>
> > **Returns**
> > The moles of solvent in the solution.

get_osmolarity(*activity_correction=False*) → Quantity

> Return the osmolarity of the solution in Osm/L.
>
> > **Parameters**
> > **activity_correction** (`bool`) – If TRUE, the osmotic coefficient is used to calculate the osmolarity. This correction is appropriate when trying to predict the osmolarity that would be measured from e.g. freezing point depression. Defaults to FALSE if omitted.

get_osmolality(*activity_correction=False*) → Quantity

> Return the osmolality of the solution in Osm/kg.
>
> > **Parameters**
> > **activity_correction** (`bool`) – If TRUE, the osmotic coefficient is used to calculate the osmolarity. This correction is appropriate when trying to predict the osmolarity that would be measured from e.g. freezing point depression. Defaults to FALSE if omitted.

get_salt() → *Salt*

> Determine the predominant salt in a solution of ions.
>
> Many empirical equations for solution properties such as activity coefficient, partial molar volume, or viscosity are based on the concentration of single salts (e.g., NaCl). When multiple ions are present (e.g., a

solution containing Na+, Cl-, and Mg+2), it is generally not possible to directly model these quantities. pyEQL works around this problem by treating such solutions as single salt solutions.

The get_salt() method examines the ionic composition of a solution and returns an object that identifies the single most predominant salt in the solution, defined by the cation and anion with the highest mole fraction. The Salt object contains information about the stoichiometry of the salt to enable its effective concentration to be calculated (e.g., if a solution contains 0.5 mol/kg of Na+ and Cl-, plus traces of H+ and OH-, the matched salt is 0.5 mol/kg NaCl).

> **Returns**
> > Salt object containing information about the parent salt.

> **See Also:**

> *get_activity()*   *get_activity_coefficient()*   *get_water_activity()*
> *get_osmotic_coefficient()* get_osmotic_pressure() get_viscosity_kinematic()

> **Examples**

```
>>> s1 = Solution([['Na+','0.5 mol/kg'],['Cl-','0.5 mol/kg']])
>>> s1.get_salt()
<pyEQL.salt_ion_match.Salt object at 0x7fe6d3542048>
>>> s1.get_salt().formula
'NaCl'
>>> s1.get_salt().nu_cation
1
>>> s1.get_salt().z_anion
-1
```

```
>>> s2 = pyEQL.Solution([['Na+','0.1 mol/kg'],['Mg+2','0.2 mol/kg'],['Cl-','0.5
→mol/kg']])
>>> s2.get_salt().formula
'MgCl2'
>>> s2.get_salt().nu_anion
2
>>> s2.get_salt().z_cation
2
```

get_salt_dict(*cutoff: float = 0.01*, *use_totals: bool = True*) → dict[str, dict]

> Returns a dict of salts that approximates the composition of the Solution. Like *components*, the dict is keyed by formula and the values are the total moles present in the solution, e.g., {"NaCl(aq)": 1}. If the Solution is pure water, the returned dict contains only 'HOH'.

> **Parameters**

> - **cutoff** – Lowest salt concentration to consider. Analysis will stop once the concentrations of Salts being analyzed goes below this value. Useful for excluding analysis of trace anions.

> - **use_totals** – Whether to base the analysis on total element concentrations or individual species concentrations.

Notes

Salts are identified by pairing the predominant cations and anions in the solution, in descending order of their respective equivalent amounts.

Many empirical equations for solution properties such as activity coefficient, partial molar volume, or viscosity are based on the concentration of single salts (e.g., NaCl). When multiple ions are present (e.g., a solution containing Na+, Cl-, and Mg+2), it is generally not possible to directly model these quantities.

The get_salt_dict() method examines the ionic composition of a solution and simplifies it into a list of salts. The method returns a dictionary of Salt objects where the keys are the salt formulas (e.g., 'NaCl'). The Salt object contains information about the stoichiometry of the salt to enable its effective concentration to be calculated (e.g., 1 M MgCl2 yields 1 M Mg+2 and 2 M Cl-).

> **Parameters**
>
> - **None** –
>
> - **Returns** –
>
> - **-------** –
>
> - **dict** – A dictionary of Salt objects, keyed to the salt formula
>
> - **Also** (*See*) –
>
> - **--------** –

:param *get_activity()*: :param *get_activity_coefficient()*: :param *get_water_activity()*: :param *get_osmotic_coefficient()*: :param get_osmotic_pressure(): :param get_viscosity_kinematic():

equilibrate(***kwargs*) → None

Update the composition of the Solution using the thermodynamic engine. Any kwargs specified are passed through to self.engine.equilibrate()

> **Returns**
> Nothing. The .components attribute of the Solution is updated.

get_activity_coefficient(*solute: str*, *scale: Literal['molal', 'molar', 'fugacity', 'rational'] = 'molal'*) → Quantity

Return the activity coefficient of a solute in solution.

The model used to calculate the activity coefficient is determined by the Solution's equation of state engine.

> **Parameters**
>
> - **solute** – The solute for which to retrieve the activity coefficient
>
> - **scale** – The activity coefficient concentration scale
>
> - **verbose** – If True, pyEQL will print a message indicating the parent salt that is being used for activity calculations. This option is useful when modeling multicomponent solutions. False by default.
>
> **Returns**
> the activity coefficient as a dimensionless pint Quantity
>
> **Return type**
> Quantity

get_activity(*solute: [str](), scale: [Literal]()['molal', 'molar', 'rational'] = 'molal'*) → Quantity

Return the thermodynamic activity of the solute in solution on the chosen concentration scale.

Parameters

- **solute** – String representing the name of the solute of interest

- **scale** – The concentration scale for the returned activity. Valid options are "molal", "molar", and "rational" (i.e., mole fraction). By default, the molal scale activity is returned.

- **verbose** – If True, pyEQL will print a message indicating the parent salt that is being used for activity calculations. This option is useful when modeling multicomponent solutions. False by default.

Returns

The thermodynamic activity of the solute in question (dimensionless Quantity)

Notes

The thermodynamic activity depends on the concentration scale used [rs] . By default, the ionic strength, activity coefficients, and activities are all calculated based on the molal (mol/kg) concentration scale.

References

See also:

[get_activity_coefficient()]() [ionic_strength]() [get_salt()]()

get_osmotic_coefficient(*scale: [Literal]()['molal', 'molar', 'rational'] = 'molal'*) → Quantity

Return the osmotic coefficient of an aqueous solution.

The method used depends on the Solution object's equation of state engine.

get_water_activity() → Quantity

Return the water activity.

Returns:

Quantity :

The thermodynamic activity of water in the solution.

See Also:

[get_activity_coefficient()]() [ionic_strength]() [get_salt()]()

Notes:

Water activity is related to the osmotic coefficient in a solution containing i solutes by:

$$\ln a_w = -\Phi M_w \sum_i m_i$$

Where M_w is the molar mass of water (0.018015 kg/mol) and m_i is the molal concentration of each species.

If appropriate Pitzer model parameters are not available, the water activity is assumed equal to the mole fraction of water.

References:

Blandamer, Mike J., Engberts, Jan B. F. N., Gleeson, Peter T., Reis, Joao Carlos R., 2005. "Activity of water in aqueous systems: A frequently neglected property." *Chemical Society Review* 34, 440-458.

Examples:

```
>>> s1 = pyEQL.Solution([['Na+','0.3 mol/kg'],['Cl-','0.3 mol/kg']])
>>> s1.get_water_activity()
<Quantity(0.9900944932888518, 'dimensionless')>
```

get_chemical_potential_energy(*activity_correction: bool = True*) → Quantity

Return the total chemical potential energy of a solution (not including pressure or electric effects).

> **Parameters**
>
> > - **activity_correction** (`bool, optional`) – If True, activities will be used to calculate the true chemical potential. If False, mole fraction will be used, resulting in a calculation of the ideal chemical potential.
> >
> > - **Returns** –
> >
> > - **-------** –
> >
> > - **Quantity** – The actual or ideal chemical potential energy of the solution, in Joules.
> >
> > - **Notes** –
> >
> > - **-----** –
> >
> > - **is** (*The chemical potential energy (related to the Gibbs mixing energy)*) –
> >
> > - **follows** (*calculated as*) –
> >
> > - **math:** (..) – E = R T sum_i n_i ln a_i:
> >
> > - **or** –
> >
> > - **math:** – E = R T sum_i n_i ln x_i:

:param Where n is the number of moles of substance: :param T is the temperature in kelvin: :param : :param R the ideal gas constant: :param x the mole fraction: :param and a the activity of: :param each component.: :param Note that dissociated ions must be counted as separate components: :param : :param so a simple salt dissolved in water is a three component solution (cation: :param : :param anion: :param and water).: :param References: :param ————-: :param .. [koga] Koga: :type .. [koga] Koga: A differential approach.* Elsevier, 2007, pp. 23-37. :param Yoshikata: :type Yoshikata: A differential approach.* Elsevier, 2007, pp. 23-37. :param 2007. *Solution Thermodynamics and its Application to Aqueous Solutions: :type 2007.*

Solution Thermodynamics and its Application to Aqueous Solutions: A differential approach. Elsevier, 2007, pp. 23-37.

_get_property(*solute: str*, *name: str*) → Any | None

Retrieve a thermodynamic property (such as diffusion coefficient) for solute, and adjust it from the reference conditions to the conditions of the solution.

> **Parameters**
>
> - **solute** (`str`) – String representing the chemical formula of the solute species
>
> - **name** (`str`) – The name of the property needed, e.g. 'diffusion coefficient'
>
> - **Returns** –
>
> - `-------` –
>
> - **Quantity** (`The desired parameter or None if not found`) –

get_transport_number(*solute*, *activity_correction=False*) → Quantity

Calculate the transport number of the solute in the solution.

> **Parameters**
>
> - **solute** – String identifying the solute for which the transport number is to be calculated.
>
> - **activity_correction** – If True, the transport number will be corrected for activity following the same method used for solution conductivity. Defaults to False if omitted.
>
> **Returns**
>
> The transport number of *solute*

Notes

Transport number is calculated according to :

$$t_i = \frac{D_i z_i^2 C_i}{\sum D_i z_i^2 C_i}$$

Where C_i is the concentration in mol/L, D_i is the diffusion coefficient, and z_i is the charge, and the summation extends over all species in the solution.

If *activity_correction* is True, the contribution of each ion to the transport number is corrected with an activity factor. See the documentation for Solution.conductivity for an explanation of this correction.

References

Geise, G. M.; Cassady, H. J.; Paul, D. R.; Logan, E.; Hickner, M. A. "Specific ion effects on membrane potential and the permselectivity of ion exchange membranes."" *Phys. Chem. Chem. Phys.* 2014, 16, 21673-21681.

get_mobility(*solute: str*) → Quantity

Calculate the ionic mobility of the solute.

> **Parameters**
>
> - **solute** (`str`) – String identifying the solute for which the mobility is to be calculated.
>
> - **Returns** –
>
> - `-------` –
>
> - **float** (`The ionic mobility. Zero if the solute is not charged.`) –

Notes:

This function uses the Einstein relation to convert a diffusion coefficient into an ionic mobility [smed]

$$\mu_i = \frac{F|z_i|D_i}{RT}$$

References:

get_lattice_distance(*solute: str*) → Quantity

Calculate the average distance between molecules.

Calculate the average distance between molecules of the given solute, assuming that the molecules are uniformly distributed throughout the solution.

> **Parameters**
>
> - **solute** (*str*) – String representing the name of the solute of interest
>
> - **Returns** –
>
> - **-------** –
>
> - **Quantity** (*The average distance between solute molecules*) –
>
> - **Examples** –
>
> - **--------** –
>
> - **Solution([['Na+'** (*>>> soln =*) –
>
> - **mol/kg']** (*'0.5*) –
>
> - **['Cl-'** –
>
> - **mol/kg']])** (*'0.5*) –
>
> - **soln.get_lattice_distance('Na+')** (*>>>*) –
>
> - **nanometer** (*1.492964....*) –
>
> - **Notes** –
>
> - **-----** –
>
> - **follows** (*The lattice distance is related to the molar concentration as*) –
>
> - **math:** (*..*) – d = (C_i N_A) ^ {-{1 over 3}}:

as_dict() → dict

Convert the Solution into a dict representation that can be serialized to .json or other format.

classmethod from_dict(*d: dict*) → Solution

Instantiate a Solution from a dictionary generated by as_dict().

print(*mode: Literal['all', 'ions', 'cations', 'anions', 'neutrals'] = 'all', units: Literal['ppm', 'mol', 'mol/kg', 'mol/L', '%', 'activity'] = 'mol', places=4*)

Print details about the Solution.

> **Parameters**
>
> - **mode** – Whether to list the amounts of all solutes, or only anions, cations, any ion, or any neutral solute.

- **units** – The units to list solute amounts in. "activity" will list dimensionless activities instead of concentrations.

- **places** – The number of decimal places to round the solute amounts.

to_json() → str

Returns a json string representation of the MSONable object.

unsafe_hash()

Returns an hash of the current object. This uses a generic but low performance method of converting the object to a dictionary, flattening any nested keys, and then performing a hash on the resulting object

classmethod validate_monty_v1(*_MSONable__input_value*)

Pydantic validator with correct signature for pydantic v1.x

classmethod validate_monty_v2(*_MSONable__input_value*, *_*)

Pydantic validator with correct signature for pydantic v2.x

4.14 Module reference

These internal modules are used by `Solution` but typically are not directly accessed by the user.

4.14.1 Salt Matching module

pyEQL salt matching library.

This file contains functions that allow a pyEQL Solution object composed of individual species (usually ions) to be mapped to a solution of one or more salts. This mapping is necessary because some parameters (such as activity coefficient data) can only be determined for salts (e.g. NaCl) and not individual species (e.g. Na+)

copyright
2013-2023 by Ryan S. Kingsbury

license
LGPL, see LICENSE for more details.

class pyEQL.salt_ion_match.**Salt**(*cation*, *anion*)

Class to represent a salt.

get_effective_molality(*ionic_strength*)

Calculate the effective molality according to [mistry].

$$\frac{2I}{(\nu_+ z_+^2 + \nu_- z_-^2)}$$

Parameters
ionic_strength (`Quantity`) – The ionic strength of the parent solution, mol/kg

Returns
Quantity

Return type
the effective molality of the salt in the parent solution

4.14.2 Modeling Engines module

pyEQL engines for computing aqueous equilibria (e.g., speciation, redox, etc.).

copyright
    2013-2023 by Ryan S. Kingsbury

license
    LGPL, see LICENSE for more details.

class pyEQL.engines.**EOS**

Abstract base class for pyEQL equation of state classes.

The intent is that concrete implementations of this class make use of the standalone functions available in pyEQL.activity_correction and pyEQL.equilibrium as much as possible. This facilitates robust unit testing while allowing users to "mix and match" or customize the various models as needed.

abstract equilibrate(*solution*)

Adjust the speciation and pH of a Solution object to achieve chemical equilibrium.

The Solution should be modified in-place, likely using add_moles / set_moles, etc.

Parameters
    solution – pyEQL Solution object

Returns
    Nothing. The speciation of the Solution is modified in-place.

Raises

- **ValueError if the calculation cannot be completed, e.g. due to insufficient number of** –
- **parameters or lack of convergence.** –

abstract get_activity_coefficient(*solution*, *solute*)

Return the *molal scale* activity coefficient of solute, given a Solution object.

Parameters

- **solution** – pyEQL Solution object
- **solute** – str identifying the solute of interest

Returns
    Quantity: dimensionless quantity object

Raises

- **ValueError if the calculation cannot be completed, e.g. due to insufficient number of** –
- **parameters.** –

abstract get_osmotic_coefficient(*solution*)

Return the *molal scale* osmotic coefficient of a Solution.

> **Parameters**
> > **solution** – pyEQL Solution object

> **Returns**
> > Quantity: dimensionless molal scale osmotic coefficient

> **Raises**
> > - **ValueError if the calculation cannot be completed, e.g. due to insufficient number of** –
> > - **parameters.** –

> abstract **get_solute_volume**()
> > Return the volume of only the solutes.

> > **Parameters**
> > > **solution** – pyEQL Solution object

> > **Returns**
> > > Quantity: solute volume in L

> > **Raises**
> > > - **ValueError if the calculation cannot be completed, e.g. due to insufficient number of** –
> > > - **parameters.** –

class pyEQL.engines.**IdealEOS**

> Ideal solution equation of state engine.

> **equilibrate**(*solution*)
> > Adjust the speciation of a Solution object to achieve chemical equilibrium.

> **get_activity_coefficient**(*solution*, *solute*)
> > Return the *molal scale* activity coefficient of solute, given a Solution object.

> **get_osmotic_coefficient**(*solution*)
> > Return the *molal scale* osmotic coefficient of solute, given a Solution object.

> **get_solute_volume**(*solution*)
> > Return the volume of the solutes.

class pyEQL.engines.**NativeEOS**

> pyEQL's native EOS. Uses the Pitzer model when possible, falls back to other models (e.g. Debye-Huckel) based on ionic strength if sufficient parameters are not available.

> **equilibrate**(*solution*)
> > Adjust the speciation of a Solution object to achieve chemical equilibrium.

> **get_activity_coefficient**(*solution*, *solute*)
> > Whenever the appropriate parameters are available, the Pitzer model [may] is used. If no Pitzer parameters are available, then the appropriate equations are selected according to the following logic: [stumm].

> > I <= 0.0005: Debye-Huckel equation 0.005 < I <= 0.1: Guntelberg approximation 0.1 < I <= 0.5: Davies equation I > 0.5: Raises a warning and returns activity coefficient = 1

The ionic strength, activity coefficients, and activities are all calculated based on the molal (mol/kg) concentration scale. If a different scale is given as input, then the molal-scale activity coefficient $\gamma_\pm$ is converted according to [rbs]

$$f_\pm = \gamma_\pm * (1 + M_w \sum_i \nu_{ii})$$

$$y_\pm = m\rho_w/C\gamma_\pm$$

where $f_\pm$ is the rational activity coefficient, M_w is the molecular weight of water, the summation represents the total molality of all solute species, $y_\pm$ is the molar activity coefficient, ρ_w is the density of pure water, m and C are the molal and molar concentrations of the chosen salt (not individual solute), respectively.

> **Parameters**
>
> > - **solute** – String representing the name of the solute of interest
> >
> > - **scale** – The concentration scale for the returned activity coefficient. Valid options are "molal", "molar", and "rational" (i.e., mole fraction). By default, the molal scale activity coefficient is returned.
>
> **Returns**
> > The mean ion activity coefficient of the solute in question on the selected scale.
>
> **See also:**
>
> get_ionic_strength   get_salt   activity_correction.get_activity_coefficient_debyehuckel   activity_correction.get_activity_coefficient_guntelberg   activity_correction.get_activity_coefficient_davies activity_correction.get_activity_coefficient_pitzer

Notes

For multicomponent mixtures, pyEQL implements the "effective Pitzer model" presented by Mistry et al. [mistry]. In this model, the activity coefficient of a salt in a multicomponent mixture is calculated using an "effective molality," which is the molality that would result in a single-salt mixture with the same total ionic strength as the multicomponent solution.

$$m_{effective} = 2I$$
$$\overline{(\nu_+ z_+^2 + \nu - z_-^2)}$$

> References

get_osmotic_coefficient(*solution*)

> Return the *molal scale* osmotic coefficient of solute, given a Solution object.
>
> Osmotic coefficient is calculated using the Pitzer model. [may] If appropriate parameters for the model are not available, then pyEQL raises a WARNING and returns an osmotic coefficient of 1.
>
> If the 'rational' scale is given as input, then the molal-scale osmotic coefficient ϕ is converted according to [rbs]
>
> $$g = -\phi * M_w \sum_i \nu_{ii})/\ln x_w$$
>
> where g is the rational osmotic coefficient, M_w is the molecular weight of water, the summation represents the total molality of all solute species, and x_w is the mole fraction of water.
>
> > **Parameters**
> > > - **scale** –

- **"molal"** (*The concentration scale for the returned osmotic coefficient. Valid options are*) –

:param : :param "rational": :type "rational": i.e., mole fraction :param coefficient is returned.:

Returns

> **Quantity:**
> The osmotic coefficient

See also:

get_water_activity get_ionic_strength get_salt

Notes

For multicomponent mixtures, pyEQL adopts the "effective Pitzer model" presented by Mistry et al. [mstry]. In this approach, the osmotic coefficient of each individual salt is calculated using the normal Pitzer model based on its respective concentration. Then, an effective osmotic coefficient is calculated as the concentration-weighted average of the individual osmotic coefficients.

For example, in a mixture of 0.5 M NaCl and 0.5 M KBr, one would calculate the osmotic coefficient for each salt using a concentration of 0.5 M and an ionic strength of 1 M. Then, one would average the two resulting osmotic coefficients to obtain an effective osmotic coefficient for the mixture.

(Note: in the paper referenced below, the effective osmotic coefficient is determined by weighting using the "effective molality" rather than the true molality. Subsequent checking and correspondence with the author confirmed that the weight factor should be the true molality, and that is what is implemented in pyEQL.)

References

Examples

```
>>> s1 = pyEQL.Solution([['Na+','0.2 mol/kg'],['Cl-','0.2 mol/kg']])
>>> s1.get_osmotic_coefficient()
<Quantity(0.923715281, 'dimensionless')>
```

```
>>> s1 = pyEQL.Solution([['Mg+2','0.3 mol/kg'],['Cl-','0.6 mol/kg']],
→temperature='30 degC')
>>> s1.get_osmotic_coefficient()
<Quantity(0.891409618, 'dimensionless')>
```

> **get_solute_volume**(*solution*)
>
> > Return the volume of the solutes.

class pyEQL.engines.**PhreeqcEOS**(*phreeqc_db: Literal['vitens.dat', 'wateq4f_PWN.dat', 'pitzer.dat', 'llnl.dat', 'geothermal.dat'] = 'phreeqc.dat'*)

Engine based on the PhreeqC model, as implemented via the phreeqpython package.

> **equilibrate**(*solution*)
>
> > Adjust the speciation of a Solution object to achieve chemical equilibrium.

> **get_activity_coefficient**(*solution*, *solute*)
>
> > Return the *molal scale* activity coefficient of solute, given a Solution object.

get_osmotic_coefficient(*solution*)

> Return the *molal scale* osmotic coefficient of solute, given a Solution object.
>
> PHREEQC appears to assume a unit osmotic coefficient unless the pitzer database is used. Unfortunately, there is no easy way to access the osmotic coefficient via phreeqcpython

get_solute_volume(*solution*)

> Return the volume of the solutes.

4.14.3 Activity Correction functions

pyEQL activity correction library.

This file contains functions for computing molal-scale activity coefficients of ions and salts in aqueous solution.

Individual functions for activity coefficients are defined here so that they can be used independently of a pyEQL solution object. Normally, these functions are called from within the get_activity_coefficient method of the Solution class.

> **copyright**
> > 2013-2023 by Ryan S. Kingsbury
>
> **license**
> > LGPL, see LICENSE for more details.

pyEQL.activity_correction.**_debye_parameter_B**(*temperature='25 degC'*)

> Return the constant B used in the extended Debye-Huckel equation.
>
> > **Parameters**
> > > **temperature** (*str Quantity, optional*) – String representing the temperature of the solution. Defaults to '25 degC' if not specified.

Notes

The parameter B is equal to:

$$B = (\frac{8\pi N_A e^2}{1000\epsilon k T})^{\frac{1}{2}}$$

References

Bockris and Reddy. /Modern Electrochemistry/, vol 1. Plenum/Rosetta, 1977, p.210.

Examples:

```
>>> _debye_parameter_B()
0.3291...
```

pyEQL.activity_correction.**_debye_parameter_activity**(*temperature='25 degC'*)

> Return the constant A for use in the Debye-Huckel limiting law (base 10).
>
> > **Parameters**
> > > **temperature** (*str Quantity, optional*) – String representing the temperature of the solution. Defaults to '25 degC' if not specified.
> >
> > **Return type**
> > > Quantity The parameter A for use in the Debye-Huckel limiting law (base e)

Notes

The parameter A is equal to:

$$A^\gamma = \frac{e^3 (2\pi N_A \rho)^{0.5}}{(4\pi \epsilon_o \epsilon_r kT)^{1.5}}$$

Note that this equation returns the parameter value that can be used to calculate the natural logarithm of the activity coefficient. For base 10, divide the value returned by 2.303. The value is often given in base 10 terms (0.509 at 25 degC) in older textbooks.

References

Archer, Donald G. and Wang, Peiming. "The Dielectric Constant of Water and Debye-Huckel Limiting Law Slopes." /J. Phys. Chem. Ref. Data/ 19(2), 1990.

Examples:

```
>>> _debye_parameter_activity()
1.17499...
```

See also:

_debye_parameter_osmotic()

pyEQL.activity_correction.**_debye_parameter_osmotic**(*temperature='25 degC'*)

Return the constant A_phi for use in calculating the osmotic coefficient according to Debye-Huckel theory.

> **Parameters**
> **temperature** (*str Quantity, optional*) – String representing the temperature of the solution. Defaults to '25 degC' if not specified.

Notes

Not to be confused with the Debye-Huckel constant used for activity coefficients in the limiting law. Takes the value 0.392 at 25 C. This constant is calculated according to: [kim] [arch]

$$A^\phi = \frac{1}{3} A^\gamma$$

References

Examples:

```
>>> _debye_parameter_osmotic()
0.3916...
```

See also:

_debye_parameter_activity()

pyEQL.activity_correction.**_debye_parameter_volume**(*temperature='25 degC'*)

> Return the constant A_V, the Debye-Huckel limiting slope for apparent molar volume.
>
> > **Parameters**
> >
> > > **temperature** (*str Quantity, optional*) – String representing the temperature of the solution. Defaults to '25 degC' if not specified.
>
> ### Notes
>
> Takes the value 1.8305 cm ** 3 * kg ** 0.5 / mol ** 1.5 at 25 C. This constant is calculated according to: **[1]_**
>
> $$A_V = -2A_\phi RT[\frac{3}{\epsilon}\frac{\partial \epsilon}{\partial p} - \frac{1}{\rho}\frac{\partial \rho}{\partial p}]$$
>
> NOTE: at this time, the term in brackets (containing the partial derivatives) is approximate. These approximations give the correct value of the slope at 25 degC and produce estimates with less than 10% error between 0 and 60 degC.
>
> The derivative of epsilon with respect to pressure is assumed constant (for atmospheric pressure) at -0.01275 1/MPa. Note that the negative sign does not make sense in light of real data, but is required to give the correct result.
>
> The second term is equivalent to the inverse of the bulk modulus of water, which is taken to be 2.2 GPa. **[2]_**
>
> ### References
>
> ### See Also:
>
> _debye_parameter_osmotic

pyEQL.activity_correction.**_pitzer_B_MX**(*ionic_strength*, *alpha1*, *alpha2*, *beta0*, *beta1*, *beta2*)

> Return the B_MX coefficient for the Pitzer ion interaction model.
>
> $$B_M X = \beta_0 + \beta_1 f1(\alpha_1 I^{0.5}) + \beta_2 f2(\alpha_2 I^{0.5})$$
>
> > **Parameters**
> >
> > - **ionic_strength** (*number*) – The ionic strength of the parent solution, mol/kg
> >
> > - **alpha1** (*number*) – Coefficients for the Pitzer model, kg ** 0.5 / mol ** 0.5
> >
> > - **alpha2** (*number*) – Coefficients for the Pitzer model, kg ** 0.5 / mol ** 0.5
> >
> > - **beta0** (*number*) – Coefficients for the Pitzer model. These ion-interaction parameters are specific to each salt system.
> >
> > - **beta1** (*number*) – Coefficients for the Pitzer model. These ion-interaction parameters are specific to each salt system.
> >
> > - **beta2** (*number*) – Coefficients for the Pitzer model. These ion-interaction parameters are specific to each salt system.
> >
> > **Returns**
> >
> > > The B_MX parameter for the Pitzer ion interaction model.
> >
> > **Return type**
> >
> > > float

References

Scharge, T., Munoz, A.G., and Moog, H.C. (2012). Activity Coefficients of Fission Products in Highly Salinary Solutions of Na+, K+, Mg2+, Ca2+, Cl-, and SO42- : Cs+. /Journal of Chemical& Engineering Data (57), p. 1637-1647.

Kim, H., & Jr, W. F. (1988). Evaluation of Pitzer ion interaction parameters of aqueous electrolytes at 25 degree C. 1. Single salt parameters. Journal of Chemical and Engineering Data, (2), 177-184.

See Also:

_pitzer_f1

pyEQL.activity_correction.**_pitzer_B_phi**(*ionic_strength*, *alpha1*, *alpha2*, *beta0*, *beta1*, *beta2*)

Return the B^Phi coefficient for the Pitzer ion interaction model.

$$B^\Phi = \beta_0 + \beta1 \exp(-\alpha_1 I^{0.5}) + \beta_2 \exp(-\alpha_2 I^{0.5})$$

or

$$B^\Phi = B^\gamma - B_{MX}$$

Parameters

- **ionic_strength** (*number*) – The ionic strength of the parent solution, mol/kg

- **alpha1** (*number*) – Coefficients for the Pitzer model, kg ** 0.5 / mol ** 0.5

- **alpha2** (*number*) – Coefficients for the Pitzer model, kg ** 0.5 / mol ** 0.5

- **beta0** (*number*) – Coefficients for the Pitzer model. These ion-interaction parameters are specific to each salt system.

- **beta1** (*number*) – Coefficients for the Pitzer model. These ion-interaction parameters are specific to each salt system.

- **beta2** (*number*) – Coefficients for the Pitzer model. These ion-interaction parameters are specific to each salt system.

Returns

The B^Phi parameter for the Pitzer ion interaction model.

Return type

float

References

Scharge, T., Munoz, A.G., and Moog, H.C. (2012). Activity Coefficients of Fission Products in Highly Salinary Solutions of Na+, K+, Mg2+, Ca2+, Cl-, and SO42- : Cs+. /Journal of Chemical& Engineering Data (57), p. 1637-1647.

Kim, H., & Jr, W. F. (1988). Evaluation of Pitzer ion interaction parameters of aqueous electrolytes at 25 degree C. 1. Single salt parameters. Journal of Chemical and Engineering Data, (2), 177-184.

Beyer, R., & Steiger, M. (2010). Vapor Pressure Measurements of NaHCOO + H 2 O and KHCOO + H 2 O from 278 to 308 K and Representation with an Ion Interaction (Pitzer) Model. Journal of Chemical & Engineering Data, 55(2), 830-838. doi:10.1021/je900487a

pyEQL.activity_correction.**_pitzer_f1**(*x*)

The function of ionic strength used to calculate eta_MX in the Pitzer ion interaction model.

$$f(x) = 2[1 - (1 + x)\exp(-x)]/x^2$$

References

Scharge, T., Munoz, A.G., and Moog, H.C. (2012). Activity Coefficients of Fission Products in Highly Salinary Solutions of Na+, K+, Mg2+, Ca2+, Cl-, and SO42- : Cs+. /Journal of Chemical& Engineering Data (57), p. 1637-1647.

Kim, H., & Jr, W. F. (1988). Evaluation of Pitzer ion interaction parameters of aqueous electrolytes at 25 degree C. 1. Single salt parameters. Journal of Chemical and Engineering Data, (2), 177-184.

pyEQL.activity_correction.**_pitzer_f2**(*x*)

The function of ionic strength used to calculate beta_gamma in the Pitzer ion interaction model.

$$f(x) = -\frac{2}{x^2}[1 - (\frac{1 + x + x^2}{2})\exp(-x)]$$

References

Scharge, T., Munoz, A.G., and Moog, H.C. (2012). Activity Coefficients of Fission Products in Highly Salinary Solutions of Na+, K+, Mg2+, Ca2+, Cl-, and SO42- : Cs+. /Journal of Chemical& Engineering Data (57), p. 1637-1647.

Kim, H., & Jr, W. F. (1988). Evaluation of Pitzer ion interaction parameters of aqueous electrolytes at 25 degree C. 1. Single salt parameters. Journal of Chemical and Engineering Data, (2), 177-184.

pyEQL.activity_correction.**_pitzer_log_gamma**(*ionic_strength*, *molality*, *B_MX*, *B_phi*, *C_phi*, *z_cation*, *z_anion*, *nu_cation*, *nu_anion*, *temperature='25 degC'*, *b=<Quantity(1.2, 'kilogram ** 0.5 / mole ** 0.5')>*)

Return the natural logarithm of the binary activity coefficient calculated by the Pitzer ion interaction model.

$$\ln\gamma_{MX} = -\frac{|z_+ z_-|A^{Phi}(I^{0.5})}{(1 + bI^{0.5})} + \frac{2}{b}\ln(1 + bI^{0.5})) + +\frac{m(2\nu_+\nu_-)}{(\nu_+ + \nu_-)}(B_{MX} + B_{MX}^{\Phi}) + \frac{m^2(3(\nu_+\nu_-)^{1.5}}{(\nu_+ + \nu_-))}C_{MX}^{\Phi}$$

Parameters

- **ionic_strength** (*Quantity*) – The ionic strength of the parent solution, mol/kg

- **molality** (*Quantity*) – The concentration of the salt, mol/kg

- **B_MX** (*Quantity*) – Calculated parameters for the Pitzer ion interaction model.

- **B_phi** (*Quantity*) – Calculated parameters for the Pitzer ion interaction model.

- **C_phi** (*Quantity*) – Calculated parameters for the Pitzer ion interaction model.

- **z_cation** (*int*) – The formal charge on the cation and anion, respectively

- **z_anion** (*int*) – The formal charge on the cation and anion, respectively

- **nu_cation** (*int*) – The stoichiometric coefficient of the cation and anion in the salt

- **nu_anion** (*int*) – The stoichiometric coefficient of the cation and anion in the salt

- **temperature** (*str Quantity*) – String representing the temperature of the solution. Defaults to '25 degC' if not specified.

- **b** (`number, optional`) – Coefficient. Usually set equal to 1.2 kg ** 0.5 / mol ** 0.5 and considered independent of temperature and pressure

Returns

The natural logarithm of the binary activity coefficient calculated by the Pitzer ion interaction model.

Return type

float

References

Kim, H., & Jr, W. F. (1988). Evaluation of Pitzer ion interaction parameters of aqueous electrolytes at 25 degree C. 1. Single salt parameters. Journal of Chemical and Engineering Data, (2), 177-184.

May, P. M., Rowland, D., Hefter, G., & Königsberger, E. (2011). A Generic and Updatable Pitzer Characterization of Aqueous Binary Electrolyte Solutions at 1 bar and 25 °C. Journal of Chemical & Engineering Data, 56(12), 5066-5077. doi:10.1021/je2009329

pyEQL.activity_correction.**get_activity_coefficient_davies**(*ionic_strength*, *formal_charge=1*, *temperature='25 degC'*)

Return the activity coefficient of solute in the parent solution according to the Davies equation.

Parameters

- **formal_charge** (`int, optional`) – The charge on the solute, including sign. Defaults to +1 if not specified.

- **ionic_strength** (`Quantity`) – The ionic strength of the parent solution, mol/kg

- **temperature** (`str Quantity, optional`) – String representing the temperature of the solution. Defaults to '25 degC' if not specified.

Returns

- *Quantity* – The mean molal (mol/kg) scale ionic activity coefficient of solute, dimensionless.

- *See Also*

- *——*

- *_debye_parameter_activity*

Notes

Activity coefficient is calculated according to:

$$\ln \gamma = A^{\gamma} z_i^2 \left(\frac{\sqrt{I}}{(1 + \sqrt{I})} + 0.2I \right)$$

Valid for 0.1 < I < 0.5

References

Stumm, Werner and Morgan, James J. Aquatic Chemistry, 3rd ed,
    pp 103. Wiley Interscience, 1996.

pyEQL.activity_correction.**get_activity_coefficient_debyehuckel**(*ionic_strength*, *formal_charge=1*, *temperature='25 degC'*)

Return the activity coefficient of solute in the parent solution according to the Debye-Huckel limiting law.

    Parameters

- **formal_charge** (`int, optional`) – The charge on the solute, including sign. Defaults to +1 if not specified.

- **ionic_strength** (`Quantity`) – The ionic strength of the parent solution, mol/kg

- **temperature** (`str Quantity, optional`) – String representing the temperature of the solution. Defaults to '25 degC' if not specified.

    Returns

- *Quantity* – The mean molal (mol/kg) scale ionic activity coefficient of solute, dimensionless.

- *See Also*

- ——

- *_debye_parameter_activity*

Notes

Activity coefficient is calculated according to:

$$\ln \gamma = A^\gamma z_i^2 \sqrt{I}$$

Valid only for I < 0.005

References

Stumm, Werner and Morgan, James J. Aquatic Chemistry, 3rd ed,
    pp 103. Wiley Interscience, 1996.

pyEQL.activity_correction.**get_activity_coefficient_guntelberg**(*ionic_strength*, *formal_charge=1*, *temperature='25 degC'*)

Return the activity coefficient of solute in the parent solution according to the Guntelberg approximation.

    Parameters

- **formal_charge** (`int, optional`) – The charge on the solute, including sign. Defaults to +1 if not specified.

- **ionic_strength** (`Quantity`) – The ionic strength of the parent solution, mol/kg

- **temperature** (`str Quantity, optional`) – String representing the temperature of the solution. Defaults to '25 degC' if not specified.

    Returns

- *Quantity* – The mean molal (mol/kg) scale ionic activity coefficient of solute, dimensionless.

- *See Also*

- ——

- *_debye_parameter_activity*

Notes

Activity coefficient is calculated according to:

$$\ln \gamma = A^\gamma z_i^2 \frac{\sqrt{I}}{(1 + \sqrt{I})}$$

Valid for I < 0.1

References

Stumm, Werner and Morgan, James J. Aquatic Chemistry, 3rd ed,
    pp 103. Wiley Interscience, 1996.

pyEQL.activity_correction.**get_activity_coefficient_pitzer**(*ionic_strength*, *molality*, *alpha1*, *alpha2*, *beta0*, *beta1*, *beta2*, *C_phi*, *z_cation*, *z_anion*, *nu_cation*, *nu_anion*, *temperature='25 degC'*, *b=1.2*)

Return the activity coefficient of solute in the parent solution according to the Pitzer model.

> **Parameters**
>
> - **ionic_strength** (`Quantity`) – The ionic strength of the parent solution, mol/kg
>
> - **molality** (`Quantity`) – The molal concentration of the parent salt, mol/kg
>
> - **alpha1** (`number`) – Coefficients for the Pitzer model. This function assigns the coefficients proper units of kg ** 0.5 / mol ** 0.5 after they are entered.
>
> - **alpha2** (`number`) – Coefficients for the Pitzer model. This function assigns the coefficients proper units of kg ** 0.5 / mol ** 0.5 after they are entered.
>
> - **beta0** (`number`) – Coefficients for the Pitzer model. These ion-interaction parameters are specific to each salt system.
>
> - **beta1** (`number`) – Coefficients for the Pitzer model. These ion-interaction parameters are specific to each salt system.
>
> - **beta2** (`number`) – Coefficients for the Pitzer model. These ion-interaction parameters are specific to each salt system.
>
> - **C_phi** (`number`) – Coefficients for the Pitzer model. These ion-interaction parameters are specific to each salt system.
>
> - **z_cation** (`int`) – The formal charge on the cation and anion, respectively
>
> - **z_anion** (`int`) – The formal charge on the cation and anion, respectively
>
> - **nu_cation** (`int`) – The stoichiometric coefficient of the cation and anion in the salt
>
> - **nu_anion** (`int`) – The stoichiometric coefficient of the cation and anion in the salt
>
> - **temperature** (`str Quantity`) – String representing the temperature of the solution. Defaults to '25 degC' if not specified.

- **b** (`number, optional`) – Coefficient. Usually set equal to 1.2 and considered independent of temperature and pressure. If provided, this coefficient is assigned proper units of kg ** 0.5 / mol ** 0.5 after entry.

Returns

- *Quantity* – The mean molal (mol/kg) scale ionic activity coefficient of solute, dimensionless

- *Examples*

- *——*

- *>>> get_activity_coefficient_pitzer(0.5*ureg.Quantity('mol/kg'),0.5*ureg.Quantity('mol/kg'),1,0.5,-.0181191983,-.4625822071,.4682,.000246063,1,-1,1,1,b=1.2)*

- *0.61915...*

- *>>> get_activity_coefficient_pitzer(5.6153*ureg.Quantity('mol/kg'),5.6153*ureg.Quantity('mol/kg'),3,0.5,0.03699 0.00171868,1,-1,1,1,b=1.2)*

- *0.76331...*

- **NOTE** (*the examples below are for comparison with experimental and modeling data presented in*)

- *the May et al reference below.*

- *10 mol/kg ammonium nitrate. Estimated result (from graph) = 0.2725*

- *>>> get_activity_coefficient_pitzer(10*ureg.Quantity('mol/kg'),10*ureg.Quantity('mol/kg'),2,0,-0.01709,0.09198,0,0.000419,1,-1,1,1,b=1.2)*

- *0.22595 ...*

- *5 mol/kg ammonium nitrate. Estimated result (from graph) = 0.3011*

- *>>> get_activity_coefficient_pitzer(5*ureg.Quantity('mol/kg'),5*ureg.Quantity('mol/kg'),2,0,-0.01709,0.09198,0,0.000419,1,-1,1,1,b=1.2)*

- *0.30249 ...*

- *18 mol/kg ammonium nitrate. Estimated result (from graph) = 0.1653*

- *>>> get_activity_coefficient_pitzer(18*ureg.Quantity('mol/kg'),18*ureg.Quantity('mol/kg'),2,0,-0.01709,0.09198,0,0.000419,1,-1,1,1,b=1.2)*

- *0.16241 ...*

References

Scharge, T., Munoz, A.G., and Moog, H.C. (2012). Activity Coefficients of Fission Products in Highly Salinary Solutions of Na+, K+, Mg2+, Ca2+, Cl-, and SO42- : Cs+. /Journal of Chemical& Engineering Data (57), p. 1637-1647.

Kim, H., & Jr, W. F. (1988). Evaluation of Pitzer ion interaction parameters of aqueous electrolytes at 25 degree C. 1. Single salt parameters. Journal of Chemical and Engineering Data, (2), 177-184.

May, P. M., Rowland, D., Hefter, G., & Königsberger, E. (2011). A Generic and Updatable Pitzer Characterization of Aqueous Binary Electrolyte Solutions at 1 bar and 25 °C. Journal of Chemical & Engineering Data, 56(12), 5066-5077. doi:10.1021/je2009329

Beyer, R., & Steiger, M. (2010). Vapor Pressure Measurements of NaHCOO + H 2 O and KHCOO + H 2 O from 278 to 308 K and Representation with an Ion Interaction (Pitzer) Model. Journal of Chemical & Engineering Data, 55(2), 830-838. doi:10.1021/je900487a

See Also:

_debye_parameter_activity _pitzer_B_MX _pitzer_B_gamma _pitzer_B_phi _pitzer_log_gamma

pyEQL.activity_correction.**get_apparent_volume_pitzer**(*ionic_strength*, *molality*, *alpha1*, *alpha2*, *beta0*, *beta1*, *beta2*, *C_phi*, *V_o*, *z_cation*, *z_anion*, *nu_cation*, *nu_anion*, *temperature='25 degC'*, *b=1.2*)

Return the apparent molar volume of solute in the parent solution according to the Pitzer model.

    Parameters

- **ionic_strength** (*Quantity*) – The ionic strength of the parent solution, mol/kg

- **molality** (*Quantity*) – The molal concentration of the parent salt, mol/kg

- **alpha1** (*number*) – Coefficients for the Pitzer model. This function assigns the coefficients proper units of kg ** 0.5 / mol ** 0.5 after they are entered.

- **alpha2** (*number*) – Coefficients for the Pitzer model. This function assigns the coefficients proper units of kg ** 0.5 / mol ** 0.5 after they are entered.

- **beta0** (*number*) – Pitzer coefficients for the apparent molar volume. These ion-interaction parameters are specific to each salt system.

- **beta1** (*number*) – Pitzer coefficients for the apparent molar volume. These ion-interaction parameters are specific to each salt system.

- **beta2** (*number*) – Pitzer coefficients for the apparent molar volume. These ion-interaction parameters are specific to each salt system.

- **C_phi** (*number*) – Pitzer coefficients for the apparent molar volume. These ion-interaction parameters are specific to each salt system.

- **V_o** (*number*) – The V^o Pitzer coefficient for the apparent molar volume.

- **z_cation** (*int*) – The formal charge on the cation and anion, respectively

- **z_anion** (*int*) – The formal charge on the cation and anion, respectively

- **nu_cation** (*int*) – The stoichiometric coefficient of the cation and anion in the salt

- **nu_anion** (*int*) – The stoichiometric coefficient of the cation and anion in the salt

- **temperature** (*str Quantity*) – String representing the temperature of the solution. Defaults to '25 degC' if not specified.

- **b** (*number, optional*) – Coefficient. Usually set equal to 1.2 and considered independent of temperature and pressure. If provided, this coefficient is assigned proper units of kg ** 0.5 / mol ** 0.5 after entry.

    Returns

- *Quantity* – The apparent molar volume of the solute, cm ** 3 / mol

- *Examples*

- ——

- **NOTE** (*the example below is for comparison with experimental and modeling data presented in*)

- *the Krumgalz et al reference below.*

- *0.25 mol/kg CuSO4. Expected result (from graph) = 0.5 cm * 3 / mol*

- >>> *get_apparent_volume_pitzer(1.0*ureg.Quantity('mol/kg'),0.25*ureg.Quantity('mol/kg'),1.4,12,0.001499,-0.008124,0.2203,-0.0002589,-6,2,-2,1,1,b=1.2)*

- *0.404…*

- *1.0 mol/kg CuSO4. Expected result (from graph) = 4 cm * 3 / mol**

- >>> *get_apparent_volume_pitzer(4.0*ureg.Quantity('mol/kg'),1.0*ureg.Quantity('mol/kg'),1.4,12,0.001499,-0.008124,0.2203,-0.0002589,-6,2,-2,1,1,b=1.2)*

- *4.424…*

- *10.0 mol/kg ammonium nitrate. Expected result (from graph) = 50.3 cm * 3 / mol**

- >>> *get_apparent_volume_pitzer(10.0*ureg.Quantity('mol/kg'),10.0*ureg.Quantity('mol/kg'),2,0,0.000001742,0.0 1,1,1,b=1.2)*

- *50.286…*

- *20.0 mol/kg ammonium nitrate. Expected result (from graph) = 51.2 cm * 3 / mol**

- >>> *get_apparent_volume_pitzer(20.0*ureg.Quantity('mol/kg'),20.0*ureg.Quantity('mol/kg'),2,0,0.000001742,0.0 1,1,1,b=1.2)*

- *51.145…*

- **NOTE** (*the examples below are for comparison with experimental and modeling data presented in*)

- *the Krumgalz et al reference below.*

- *0.8 mol/kg NaF. Expected result = 0.03*

- >>> *get_apparent_volume_pitzer(0.8*ureg.Quantity('mol/kg'),0.8*ureg.Quantity('mol/kg'),2,0,0.000024693,0.00 0.000004068,-2.426,1,-1,1,1,b=1.2)*

- *0.22595 …*

References

May, P. M., Rowland, D., Hefter, G., & Königsberger, E. (2011). A Generic and Updatable Pitzer Characterization of Aqueous Binary Electrolyte Solutions at 1 bar and 25 °C. Journal of Chemical & Engineering Data, 56(12), 5066-5077. doi:10.1021/je2009329

Krumgalz, Boris S., Pogorelsky, Rita (1996). Volumetric Properties of Single Aqueous Electrolytes from Zero to Saturation Concentration at 298.15 K Represented by Pitzer's Ion-Interaction Equations. Journal of Physical Chemical Reference Data, 25(2), 663-689.

See Also:

_debye_parameter_volume _pitzer_B_MX

pyEQL.activity_correction.**get_osmotic_coefficient_pitzer**(*ionic_strength*, *molality*, *alpha1*, *alpha2*, *beta0*, *beta1*, *beta2*, *C_phi*, *z_cation*, *z_anion*, *nu_cation*, *nu_anion*, *temperature='25 degC'*, *b=1.2*)

Return the osmotic coefficient of water in an electrolyte solution according to the Pitzer model.

> **Parameters**

> > - **ionic_strength** (*Quantity*) – The ionic strength of the parent solution, mol/kg

- **molality** (`Quantity`) – The molal concentration of the parent salt, mol/kg

- **alpha1** (`number`) – Coefficients for the Pitzer model. This function assigns the coefficients proper units of kg ** 0.5 / mol ** 0.5 after they are entered.

- **alpha2** (`number`) – Coefficients for the Pitzer model. This function assigns the coefficients proper units of kg ** 0.5 / mol ** 0.5 after they are entered.

- **beta0** – Coefficients for the Pitzer model. These ion-interaction parameters are specific to each salt system.

- **beta1** – Coefficients for the Pitzer model. These ion-interaction parameters are specific to each salt system.

- **beta2** – Coefficients for the Pitzer model. These ion-interaction parameters are specific to each salt system.

- **C_phi** – Coefficients for the Pitzer model. These ion-interaction parameters are specific to each salt system.

- **z_cation** (`int`) – The formal charge on the cation and anion, respectively

- **z_anion** (`int`) – The formal charge on the cation and anion, respectively

- **nu_cation** (`int`) – The stoichiometric coefficient of the cation and anion in the salt

- **nu_anion** (`int`) – The stoichiometric coefficient of the cation and anion in the salt

- **temperature** (`str Quantity`) – String representing the temperature of the solution. Defaults to '25 degC' if not specified.

- **b** (`number, optional`) – Coefficient. Usually set equal to 1.2 and considered independent of temperature and pressure. If provided, this coefficient is assigned proper units of kg ** 0.5 / mol ** 0.5 after entry.

Returns

- *Quantity* – The osmotic coefficient of water, dimensionless

- *Examples*

- *——*

- *Experimental value according to Beyer and Stieger reference is 1.3550*

- *>>> get_osmotic_coefficient_pitzer(10.175*ureg.Quantity('mol/kg'),10.175*ureg.Quantity('mol/kg'),1,0.5,-.0181191983,-.4625822071,.4682,.000246063,1,-1,1,1,b=1.2)*

- *1.3552 . . .*

- *Experimental value according to Beyer and Stieger reference is 1.084*

- *>>> get_osmotic_coefficient_pitzer(5.6153*ureg.Quantity('mol/kg'),5.6153*ureg.Quantity('mol/kg'),3,0.5,0.0369*
  0.00171868,1,-1,1,1,b=1.2)

- *1.0850 . . .*

- **NOTE** (*the examples below are for comparison with experimental and modeling data presented in*)

- *the May et al reference below.*

- *10 mol/kg ammonium nitrate. Estimated result (from graph) = 0.62*

- *>>> get_osmotic_coefficient_pitzer(10*ureg.Quantity('mol/kg'),10*ureg.Quantity('mol/kg'),2,0,-0.01709,0.09198,0,0.000419,1,-1,1,1,b=1.2)*

- *0.6143 . . .*

- *5 mol/kg ammonium nitrate. Estimated result (from graph) = 0.7*

- *>>> get_osmotic_coefficient_pitzer(5*ureg.Quantity('mol/kg'),5*ureg.Quantity('mol/kg'),2,0,-0.01709,0.09198,0,0.000419,1,-1,1,1,b=1.2)*

- *0.6925 . . .*

- *18 mol/kg ammonium nitrate. Estimated result (from graph) = 0.555*

- *>>> get_osmotic_coefficient_pitzer(18*ureg.Quantity('mol/kg'),18*ureg.Quantity('mol/kg'),2,0,-0.01709,0.09198,0,0.000419,1,-1,1,1,b=1.2)*

- *0.5556 . . .*

References

Scharge, T., Munoz, A.G., and Moog, H.C. (2012). Activity Coefficients of Fission Products in Highly Salinary Solutions of Na+, K+, Mg2+, Ca2+, Cl-, and SO42- : Cs+. /Journal of Chemical& Engineering Data (57), p. 1637-1647.

Kim, H., & Jr, W. F. (1988). Evaluation of Pitzer ion interaction parameters of aqueous electrolytes at 25 degree C. 1. Single salt parameters. Journal of Chemical and Engineering Data, (2), 177-184.

May, P. M., Rowland, D., Hefter, G., & Königsberger, E. (2011). A Generic and Updatable Pitzer Characterization of Aqueous Binary Electrolyte Solutions at 1 bar and 25 °C. Journal of Chemical & Engineering Data, 56(12), 5066-5077. doi:10.1021/je2009329

Beyer, R., & Steiger, M. (2010). Vapor Pressure Measurements of NaHCOO + H 2 O and KHCOO + H 2 O from 278 to 308 K and Representation with an Ion Interaction (Pitzer) Model. Journal of Chemical & Engineering Data, 55(2), 830-838. doi:10.1021/je900487a

See Also:

_debye_parameter_activity _pitzer_B_MX _pitzer_B_gamma _pitzer_B_phi _pitzer_log_gamma

4.14.4 Speciation functions

pyEQL methods for chemical equilibrium calculations (e.g. acid/base, reactions, redox, complexation, etc.).

NOTE: these methods are not currently used but are here for the future.

copyright
2013-2023 by Ryan S. Kingsbury

license
LGPL, see LICENSE for more details.

pyEQL.equilibrium.**adjust_temp_arrhenius**(*rate_constant*, *activation_energy*, *temperature*, *reference_temperature=<Quantity(25, 'degree_Celsius')>*)

(float,float,number, optional number) -> float.

Adjust a reaction equilibrium constant from one temperature to another.

Parameters

- **rate_constant** (*Quantity*) – The parameter value (usually a rate constant) being adjusted

- **activation_energy** (*Quantity*) – The activation energy of the process, in kJ/mol

- **temperature** (*Quantity*) – the desired reaction temperature.

- **reference_temperature** (*Quantity, optional*) – the temperature at which equilibrium_constant is valid Defaults to 25 degrees C if omitted.

Returns

- *Quantity* – The adjusted reaction equilibrium constant

- *See Also*

- *——*

- *kelvin*

Notes

This function implements the Arrhenius equation to adjust measured rate constants to other temperatures. TODO - add better reference

$$ln($$
$$fracK2K1 =$$
$$fracE_aR($$
$$frac1T_1 -$$
$$frac1T_2)$$

References

http://chemwiki.ucdavis.edu/Physical_Chemistry/Kinetics/Reaction_Rates/Temperature_Dependence_of_Reaction_Rates/Arrhenius_Equation

Examples:

```
>>> adjust_temp_arrhenius(7,900*ureg.Quantity('kJ/mol'),37*ureg.Quantity('degC'),
↪97*ureg.Quantity('degC'))
1.8867225...e-24
```

pyEQL.equilibrium.**adjust_temp_pitzer**(*c1, c2, c3, c4, c5, temp, temp_ref=<Quantity(298.15, 'kelvin')>*)

Calculate a parameter for the Pitzer model based on temperature-dependent coefficients c1,c2,c3,c4,and c5.

Parameters

- **c1** (*float*) – Temperature-dependent coefficients for the pitzer parameter of interest.

- **c2** (*float*) – Temperature-dependent coefficients for the pitzer parameter of interest.

- **c3** (*float*) – Temperature-dependent coefficients for the pitzer parameter of interest.

- **c4** (*float*) – Temperature-dependent coefficients for the pitzer parameter of interest.

- **c5** (*float*) – Temperature-dependent coefficients for the pitzer parameter of interest.

- **temp** (*Quantity*) – The temperature at which the Pitzer parameter is to be calculated

- **temp_ref** (*Quantity, optional*) – The reference temperature on which the parameters are based. 298.15 K if omitted.

- **documentation** (*As described in the PHREEQC*) –

pyEQL.equilibrium.**adjust_temp_vanthoff**(*equilibrium_constant*, *enthalpy*, *temperature*, *reference_temperature=<Quantity(25, 'degree_Celsius')>*)

    (float,float,number, optional number) -> float.

    Adjust a reaction equilibrium constant from one temperature to another.

> **Parameters**
>
> - **equilibrium_constant** (*float*) – The reaction equilibrium constant for the reaction
> - **enthalpy** (*Quantity*) – The enthalpy change (delta H) for the reaction in kJ/mol. Assumed independent of temperature (see Notes).
> - **temperature** (*Quantity*) – the desired reaction temperature in degrees Celsius
> - **reference_temperature** (*Quantity, optional*) – the temperature at which equilibrium_constant is valid. (25 degrees C if omitted).
>
> **Returns**
>   adjusted reaction equilibrium constant
>
> **Return type**
>   float

Notes

This function implements the Van't Hoff equation to adjust measured equilibrium constants to other temperatures.

$$ln(K2/K1) = \frac{\delta H}{R}(\frac{1}{T_1} - \frac{1}{T_2})$$

This implementation assumes that the enthalpy is independent of temperature over the range of interest.

References

Stumm, Werner and Morgan, James J. Aquatic Chemistry, 3rd ed, pp 53.
    Wiley Interscience, 1996.

Examples:

```
>>> adjust_temp_vanthoff(0.15,ureg.Quantity('-197.6 kJ/mol'),ureg.Quantity('42 degC
↪'),ureg.Quantity(' 25degC'))
0.00203566...
```

If the 'ref_temperature' parameter is omitted, a default of 25 C is used.

```
>>> adjust_temp_vanthoff(0.15,ureg.Quantity('-197.6 kJ/mol'),ureg.Quantity('42 degC
↪'))
0.00203566...
```

pyEQL.equilibrium.**alpha**(*n*, *pH*, *pKa_list*)

> **Returns the acid-base distribution coefficient (alpha) of an acid in the**
>   n-deprotonated form at a given pH.
>
> > **Parameters**

- **n** (*int*) – The number of protons that have been lost by the desired form of the acid. Also the subscript on the alpha value. E.g. for bicarbonate (HCO3-), n=1 because 1 proton has been lost from the fully-protonated carbonic acid (H2CO3) form.

- **pH** (*float or int*) – The pH of the solution.

- **pKa_list** (*list of floats or ints*) – The pKa values (negative log of equilibrium constants) for the acid of interest. There must be a minimum of n pKa values in the list.

Returns

The fraction of total acid present in the specified form.

Return type

float

Notes

The acid-base cient is calculated as follows: [stm]

$$\alpha_n = \frac{term_n}{[H+]^n + k_{a1}[H+]^{n-1} + k_{a1}k_{a2}[H+]^{n-2}...k_{a1}k_{a2}...k_{an}}$$

Where :math: ' erm_n' refers to the nth term in the denominator, starting from 0

References

Examples:

```
>>> alpha(1,8,[4.7])
0.999...
```

The sum of all alpha values should equal 1

```
>>> alpha(0,8,[6.35,10.33])
0.021...
>>> alpha(1,8,[6.35,10.33])
0.979...
>>> alpha(2,8,[6.35,10.33])
2.043...e-09
```

If pH is equal to one of the pKa values the function should return 0.5.

```
>>> alpha(1,6.35,[6.35,10.33])
0.5
```

pyEQL.equilibrium.**equilibrate_phreeqc**(*solution*, *phreeqc_db: Literal['vitens.dat', 'wateq4f_PWN.dat', 'pitzer.dat', 'llnl.dat', 'geothermal.dat'] = 'vitens.dat'*)

Adjust the speciation of a Solution object to achieve chemical equilibrium.

Parameters

phreeqc_db – Name of the PHREEQC database file to use for solution thermodynamics and speciation calculations. Generally speaking, *llnl.dat* is recommended for moderate salinity water and prediction of mineral solubilities, *wateq4f_PWN.dat* is recommended for low to moderate salinity waters. It is similar to vitens.dat but has many more species. *pitzer.dat* is recommended when accurate activity coefficients in solutions above 1 M TDS are desired, but it has fewer species than the other databases. *llnl.dat* and *geothermal.dat* may offer improved prediction of LSI.

4.14.5 Utilities

pyEQL utilities

> **copyright**
> 2023 by Ryan S. Kingsbury
>
> **license**
> LGPL, see LICENSE for more details.

class pyEQL.utils.**FormulaDict**(*dict=None, /, **kwargs*)

> Automatically converts keys on get/set using pymatgen.core.Ion.from_formula(key).reduced_formula.
>
> This allows getting/setting/updating of Solution.components using flexible formula notation (e.g., "Na+", "Na+1", "Na^{+}" all have the same effect)

pyEQL.utils.**format_solutes_dict**(*solute_dict: dict, units: str*)

> Formats a dictionary of solutes by converting the amount to a string with the provided units suitable for passing to use with the Solution class. Note that all solutes must be given in the same units.
>
> **Parameters**
>
> - **solute_dict** – The dictionary to format. This must be of the form dict{str: Number} e.g. {"Na+": 0.5, "Cl-": 0.9}
>
> - **units** – The units to use for the solute. e.g. "mol/kg"
>
> **Returns**
> A formatted solute dictionary.
>
> **Raises**
> **TypeError if solute_dict is not a dictionary.** –

pyEQL.utils.**standardize_formula**(*formula: str*)

> Convert a chemical formula into standard form.
>
> **Parameters**
> **formula** – the chemical formula to standardize.
>
> **Returns**
> A standardized chemical formula
>
> **Raises**
> **ValueError if formula cannot be processed or is invalid.** –

Notes

Currently this method standardizes formulae by passing them through pymatgen.core.ion.Ion.reduced_formula(). For ions, this means that 1) the charge number will always be listed explicitly and 2) the charge number will be enclosed in square brackets to remove any ambiguity in the meaning of the formula. For example, 'Na+', 'Na+1', and 'Na^{+}' will all standardize to "Na[+1]"

4.15 Contributing to pyEQL

4.15.1 Reporting Issues

You can help the project simply by using pyEQL and comparing the output to experimental data and/or other models and tools. If you encounter any bugs, packaging issues, feature requests, comments, or questions, please report them using the issue tracker on github.

4.15.2 Contributing Code

To contribute bug fixes, documentation enhancements, or new code, please fork pyEQL and send us a pull request. It's not as hard as it sounds! Beginning with version 0.6.0, we follow the GitHub flow workflow model.

Hacking pyEQL, step by step

1. Fork the pyEQL repository on Github

2. Clone your repository to a directory of your choice:

   ```
   git clone https://github.com/<username>/pyEQL
   ```

3. Install the package and the test dependencies by running the following command from the repository directory:

   ```
   pip install -e '.[testing]``
   ```

4. Create a branch for your work. Preferably, start your branch name with "feature-", "fix-", or "doc-" depending on whether you are contributing **bug fixes**, **documentation** or a **new feature**, e.g. prefix your branch with "fix-" or "doc-" as appropriate:

   ```
   git checkout -b mybranch
   ```

   or

   ```
   git checkout -b doc-mydoc
   ```

   or

   ```
   git checkout -b feature-myfeature
   ```

5. Make changes to the code until you're satisfied.

6. Push your work back to Github:

   ```
   git push origin feature-myfeature
   ```

7. Create a pull request with your changes. See this tutorial for instructions.

4.15.3 Guidelines

Please abide by the following guidelines when contributing code to `pyEQL`:

- All changes you make to quacc should be accompanied by unit tests and should not break existing tests. To run the full test suite, run `pytest tests/` from the repository directory.

- Code coverage should be maintained or increase. Each PR will report code coverage after the tests pass, but you can check locally using pytest-cov, by running `pytest --cov tests/`

- All code should include type hints and have internally consistent documentation for the inputs and outputs.

- Use Google style docstrings

- Lint your code with ruff by running `ruff check --fix src/` from the repo directory. Alternatively, you can install the `pre-commit` hooks by running `pre-commit install` from the repository directory. This will prevent committing new changes until all linting errors are fixed.

- Update the `CHANGELOG.md` file.

- Ask questions and be open to feedback!

4.15.4 Documentation

Improvements to the documentation are most welcome! Our documentation system uses `sphinx` with the Materials for Sphinx theme. To edit the documentation locally, run `tox -e autodocs` from the repository root directory. This will serve the documents to http://localhost:8000/ so you can view them in your web browser. When you make changes to the files in the `docs/` directory, the documentation will automatically rebuild and update in your browser (you might have to refresh the page to see changes).

4.15.5 Changelog

We keep a `CHANGELOG.md` file in the base directory of the repository. Before submitting your PR, be sure to update the `CHANGELOG.md` file under the "Unreleased" section with a brief description of your changes. Our `CHANGELOG.md` file lossely follows the Keep a Changelog format, beginning with `v0.6.0`.

4.16 Contributors

pyEQL was originally written by Prof. Ryan Kingsbury (@rkingsbury) and is primarily developed and maintained by the Kingsbury Lab at Princeton University.

Other contributors, listed alphabetically, are:

- @DhruvDuseja
- Hernan Grecco (@hgrecco)

(If you think that your name belongs here, please let the maintainer know)

4.17 License

Copyright (c) 2013-2023 Ryan S. Kingsbury

pyEQL is free software; you can redistribute it and/or modify it under the terms of the GNU Lesser General Public License as published by the Free Software Foundation; version 3.0 of the License.

A copy of the GNU Lesser General Public License is included in the pyEQL package in the file COPYING. If you did not receive this copy, write to the Free Software Foundation, Inc., 51 Franklin St, Fifth Floor, Boston, MA 02110-1301, USA.

Data included in pyEQL's databases (/database directory) is used with permission of the authors. If you wish to redistribute these databases as part of a derived work, you are advised to contact the authors or publishers for copyright information.

This program is distributed in the hope that it will be useful, but WITHOUT ANY WARRANTY; without even the implied warranty of MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE. See the GNU Lesser General Public License for more details.

BIBLIOGRAPHY

[stm]   Stumm, Werner and Morgan, James J. Aquatic Chemistry, 3rd ed, pp 165. Wiley Interscience, 1996.

[sata]   Sata, Toshikatsu. Ion Exchange Membranes: Preparation, Characterization, and Modification. Royal Society of Chemistry, 2004, p. 10.

[wk]   http://en.wikipedia.org/wiki/Osmotic_pressure#Derivation_of_osmotic_pressure

[rs]   Robinson, R. A.; Stokes, R. H. Electrolyte Solutions: Second Revised Edition; Butterworths: London, 1968, p.32.

[smed]   Smedley, Stuart I. The Interpretation of Ionic Conductivity in Liquids. Plenum Press, 1980.

[mistry] Mistry, K. H.; Hunter, H. a.; Lienhard V, J. H. Effect of composition and nonideal solution behavior on desalination calculations for mixed electrolyte solutions with comparison to seawater. Desalination 2013, 318, 34-47.

[may]   May, P. M., Rowland, D., Hefter, G., & Königsberger, E. (2011). A Generic and Updatable Pitzer Characterization of Aqueous Binary Electrolyte Solutions at 1 bar and 25 °C. *Journal of Chemical & Engineering Data*, 56(12), 5066-5077. doi:10.1021/je2009329

[stumm]   Stumm, Werner and Morgan, James J. *Aquatic Chemistry*, 3rd ed, pp 165. Wiley Interscience, 1996.

[rbs]   Robinson, R. A.; Stokes, R. H. Electrolyte Solutions: Second Revised Edition; Butterworths: London, 1968, p.32.

[mistry] Mistry, K. H.; Hunter, H. a.; Lienhard V, J. H. Effect of composition and nonideal solution behavior on desalination calculations for mixed electrolyte solutions with comparison to seawater. Desalination 2013, 318, 34-47.

[may]   May, P. M., Rowland, D., Hefter, G., & Königsberger, E. (2011). A Generic and Updatable Pitzer Characterization of Aqueous Binary Electrolyte Solutions at 1 bar and 25 °C. Journal of Chemical & Engineering Data, 56(12), 5066-5077. doi:10.1021/je2009329

[rbs]   Robinson, R. A.; Stokes, R. H. Electrolyte Solutions: Second Revised Edition; Butterworths: London, 1968, p.32.

[mstry]   Mistry, K. H.; Hunter, H. a.; Lienhard V, J. H. Effect of composition and nonideal solution behavior on desalination calculations for mixed electrolyte solutions with comparison to seawater. Desalination 2013, 318, 34-47.

[kim]   Kim, Hee-Talk and Frederick, William Jr, 1988. "Evaluation of Pitzer Ion Interaction Parameters of Aqueous Electrolytes at 25 C. 1. Single Salt Parameters," *J. Chemical Engineering Data* 33, pp.177-184.

[arch]   Archer, Donald G. and Wang, Peiming. "The Dielectric Constant of Water and Debye-Huckel Limiting Law Slopes." /J. Phys. Chem. Ref. Data/ 19(2), 1990.

[stm]   Stumm, Werner and Morgan, James J. Aquatic Chemistry, 3rd ed, pp 127-130. Wiley Interscience, 1996.

PYTHON MODULE INDEX

p

Symbols

A

B

C

D

E

F

G

T

U

V