Compilation of Thermal Models Applicable to Energy Piles

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Contents

Introduction

The main aim of this document is to compile thermal models that can be used to carry out thermal dimensioning of energy pile foundations when the tailored energy pile dimensioning tool developed at Centrum Pæle A/S (Alberdi-Pagola, 2018), Denmark, is not available. This tool is named as the “Centrum Pæle tool” hereon.

Notice that the main content of this document is built on top of the literature review provided in (Alberdi-Pagola, 2018) which has been updated with recent references. Besides, this document does not treat models that can be used for modelling thermo-mechanical aspects of energy piles.

Having access to models that can reproduce the thermal behaviour of energy piles (at different levels of detail) is very useful, because, among others, they facilitate the thermal dimensioning (sizing) of energy pile foundations. A dimensioning involves a calculation of the energy (i.e., heating and/or cooling needs) that an energy pile foundation of a certain building at a certain location can supply. Dimensioning tools can also assist with the selection of the heat pump size or with the optimisation of the location of the energy piles within the foundation. Besides, models can also be used, e.g., to predict the performance of the installation during time and, this way, assess economic aspects.

Thermal models can be used to perform system sizing for different levels of details:

1. A feasibility analysis gives an indication of the heating and cooling needs that can be supplied per meter of energy pile (W/m·year and kWh/m·year). Usually, this type of analyses take place at an early stage of the project, during initial decision making. At this stage, a lot of details involving the building are not known (e.g., final heating and cooling needs, specific dimensions and location of piles, etc.) but, still, the clients need to have an indication of the energy pile coverage. For this type of calculations, there are different tools available. Laloui & Rotta Loria (2018) and SIA (2005) have developed a scheme that leads the engineer through different steps. Depending on the thermal conductivity of the soil and the working mode (heating, cooling, and proportion of thermal recharge of the soil), the heat extraction can range between 25 - 50 W/m while the injection should not exceed 30 W/m. Another methodology is provided in (Ferrantelli et al., 2020), where the condenser yield per pile meter is determined by specifying only building heat load and geometric characteristics of the energy piles system.

2. As the project advances and more details are known (e.g., building needs, foundation arrangement, soil conditions) the accuracy level of the analyses can be improved. Here, we could find models that, among other aspects, can consider the thermal interaction between piles and provide ground-loop temperatures over installation lifetime. E.g., Centrum Pæle’s tool could fit in this category. Please, notice that the Centrum Tool considers a constant Seasonal Performance Factor SPF. This model gives an indication of the heating and cooling loads that can be supplied with an energy pile foundation, but to predict the most that we can obtain from the GSHP installation as a whole, the model should be refined (see next level). Ideally, to investigate energy pile foundations, we would use models developed for energy piles. However, this might not always be possible (because we do not have the resources to build the models) or it might not be necessary (because we can accept a loss of accuracy as long as we gain speed using Borehole Heat Exchanger BHE models). The next sections provide more details about these models.

3. In a third category, we could find very detailed and comprehensive models where the performance of the installation is calculated dynamically (every time step, e.g., hourly and the SPF can be calculated accordingly) and where the heating and cooling units are also modelled in detail. These models require higher computation capacity and highly qualified engineers and are not treated here.

Thermal Models for Energy Piles

The temperature disturbance in the pile-soil system depends, mainly, on i) the thermal properties of the concrete (also to consider the thermal inertia of the pile concrete, primarily in the short term) and the surrounding soil, ii) the geometry of the pile and iii) the foundation pile arrangement (the long-term performance of energy pile foundations must consider the thermal interaction between piles). To calculate the ground loop fluid temperature, besides, the thermal properties of the geothermal pipes and their position, the heat carrier fluid flow conditions and the initial undisturbed ground temperature need to be considered. This section overviews the existing options for thermal analysis of energy pile foundations.

The Centrum Pæle tool (Alberdi-Pagola, 2018) has been implemented in MATLAB and Python. This is a tailored tool developed to carry out feasibility analyses and thermally design irregular patterns of multiple precast energy piles. It is used to predict long-term average ground loop temperatures at a given building.

PILESIM (Pahud, 1999) is an experimentally validated (Pahud & Hubbuch, 2007) commercial software for energy piles, where the duct storage model (Hellström, 1991) is implemented, however it does not take irregular patterns into consideration.

(Makasis et al., 2018) use machine learning to find the maximum energy that can be provided by a specified energy pile foundation, yet the method has not yet been applied to irregular pile patterns.

To allow the analysis of irregular pile configurations and take into account the variety in types of piles, there are several methods and studies:

1. Finite element modelling (FEM): 3D simulation-based analysis of multiple pile heat exchanger foundations is highly impractical due to excessive computation times and simpler models are required for real applications.

2. Line and cylindrical source finite solutions suggested in (Bandos et al., 2014).

3. From a practical point of view, using semi-empirical models for analysing the thermal performance of energy pile foundations is recommended. Centrum Pæle's tool uses this approach, based on the methodology suggested in (Fleur Loveridge & Powrie, 2013, 2014). Semi empirical equations for pile and concrete thermal responses can be developed to account for axial effects ignored by the infinite source approaches. These semi-empirical temperature response curves (g-functions first introduced by (Eskilson, 1987) combined with time (J D Spitler & Bernier, 2016) and spatial superposition (Massimo Cimmino et al., 2013) can consider influences between piles placed in irregular arrangements. This approach is very flexible, but it is also based on analytical or FEM models.

Thermal Models for BHEs

The thermal dimensioning of energy pile foundations has been typically addressed by methods developed for borehole heat exchangers. Some of these models are implemented in commercial software, such as: GLHEPro (Jeffrey D Spitler, 2000), EED (Building Physics, 2017), LoopLink PRO (Geo Connections, 2018), GLD (Gaia Geothermal, 2016) or the ASHRAE method accompanied by an open source excel spreadsheet (ASHRAE, 2007; Philippe et al., 2010).

However, models developed for BHEs are not always well suited to take into account the singularities of energy pile arrangements. Still, when energy pile thermal models are not available, it might be easier (or more approachable) to handle BHE models, even though we might lose accuracy, because BHEs have been around for a longer time and their analysis is more developed. The previously mentioned software use some of the analytical and/or numerical approaches commented below:

Infinite line and cylinder solutions described in (F Loveridge, 2012; Vieira et al., 2017) are not well suited to model long-term analysis of energy piles because axial effects are not taken into account.

To consider the thermal interaction between piles (Eskilson, 1987) presented g-functions where the thermal interaction is calculated by spatial superposition of single BHE temperatures, based on a finite difference model.

As presented for energy piles, multiple ground heat exchanger g-functions can also be calculated by spatial superposition of analytical solutions for single ground heat exchangers that permit calculation of the radial temperature distribution (Massimo Cimmino et al., 2013; Massimo Cimmino & Bernier, 2014; M. Fossa & Rolando, 2014; Marco Fossa, 2011; Marco Fossa et al., 2009; Katsura et al., 2008)

A different approach is the ASHRAE method, where the temperature penalty concept is defined to account for thermal interactions between individual heat exchangers (Bernier et al., 2004, 2008; Marco Fossa & Rolando, 2015; Philippe et al., 2010). However, the spreadsheet is limited to 0.1 m radius BHEs and maximum 144 BHEs.

Multiple heat exchanger g-functions have also been calculated by means of finite element modelling (Acuña et al., 2012; Monzó, 2018).

Finally, one of the most recent developments is the open source code implemented in Python by (M. Cimmino, 2018). This toolbox uses analytical methods, based on the finite line source solution and it allows to play with different BHE configuration, boundary conditions and load aggregation methods. A summary and tips for installation of this code is provided in appendix A.1.

Mention to Energy Geostructures

Just a brief mention to other Energy Geostructures. Basically, any geostructure in contact with the soil can be turned into an energy geostructure (Laloui & Di Donna, 2013; Di Donna et al., 2017; Loveridge et al., 2020). Basement walls, tunnel linings, ground anchors, base slabs, etc. can be converted by embedded geothermal pipes through which the heat carried fluid circulates. The basic knowledge of precast energy piles can be applied to in situ energy piles (and other energy geostructures). The references cited below provide quick dimensioning approaches:

- Energy walls (Di Donna et al., 2016).
- Energy tunnels (Barla et al., 2019).
- Energy sewage.
- Energy ground anchors.
- Energy base slabs (Lee et al., 2021).
- Energy shallow foundations.

Discussion and Conclusion

The main aspect considered when modelling energy piles, which is not considered in BHE modelling, is the thermal inertia of the pile concrete, primarily in the short term. According to (Fleur Loveridge & Powrie, 2013, 2014) including the transient temperature change in the concrete results in a reduction of the range of calculated fluid temperatures and, therefore, 10% more energy is available in the system, compared to steady state approaches. I.e., steady state approaches overestimate the range of temperature response. This is relevant for energy piles because their operational temperature range is tighter than that of BHEs: 2 °C to 30 °C and <0 °C to >50 °C for energy piles and BHEs, respectively.

Steady state approaches are, hence, more conservative. And being conservative might be a good strategy for feasibility analyses. However, as projects progress, it is recommended to use methods that consider the transient temperature response of the pile.

References

Acuña, J., Fossa, M., Monzó, P., & Palm, B. (2012). Numerically Generated g-functions for Ground Coupled Heat Pump Applications. *Proc. Proceedings of the COMSOL Conference in Milan*. https://www.comsol.pt/paper/download/152309/acuna_paper.pdf

Alberdi-Pagola, M. (2018). *Design and performance of energy pile foundations*. Aalborg University.

ASHRAE. (2007). *2007 ASHRAE Handbook - Heating, Ventilating, and Air-Conditioning Applications (I-P Edition)*. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. http://www.knovel.com/web/portal/browse/display?_EXT_KNOVEL_DISPLAY_bookid=2397

Bandos, T. V, Campos-Celador, Á., López-González, L. M., & Sala-Lizarraga, J. M. (2014). Finite cylinder-source model for energy pile heat exchangers: Effects of thermal storage and vertical temperature variations. *Energy*, 78, 639–648. https://doi.org/http://dx.doi.org/10.1016/j.energy.2014.10.053

Barla, M., Di Donna, A., & Insana, A. (2019). A novel real-scale experimental prototype of energy tunnel. *Tunnelling and Underground Space Technology*, 87, 1–14. https://doi.org/10.1016/j.tust.2019.01.024

Bernier, M. A., Chahla, A., & Pinel, P. (2008). Long-Term Ground-Temperature Changes in Geo-Exchange Systems. *ASHRAE Transactions*, 114(2).

Bernier, M. A., Pinel, P., Labib, R., & Paillot, R. (2004). A Multiple Load Aggregation Algorithm for Annual Hourly Simulations of GCHP Systems. *HVAC&R Research*, 10(4), 471–487. https://doi.org/10.1080/10789669.2004.10391115

Building Physics. (2017). Earth Energy Designer EED 4. https://www.buildingphysics.com/manuals/EED4.pdf

Cimmino, M. (2018). pygfunction: an open-source toolbox for the evaluation of thermal response factors for geothermal borehole fields. *Proc. Proceedings of eSim 2018, the 10th conference of IBPSA-Canada*. 492–501. ISBN 978-2-921145-88-6

Cimmino, Massimo, & Bernier, M. (2014). A semi-analytical method to generate g-functions for geothermal bore fields. *International Journal of Heat and Mass Transfer*, 70, 641–650. https://doi.org/10.1016/j.ijheatmasstransfer.2013.11.037

Cimmino, Massimo, Bernier, M., & Adams, F. (2013). A contribution towards the determination of g-functions using the finite line source. *Applied Thermal Engineering*, 51(1), 401–412. https://doi.org/http://dx.doi.org/10.1016/j.applthermaleng.2012.07.044

Di Donna, A., Cecinato, F., Loveridge, F. A., & Barla, M. (2016). Energy performance of diaphragm walls used as heat exchangers. *Proceedings of the Institution of Civil Engineers - Geotechnical Engineering*, 170. https://doi.org/10.1680/jgeen.16.00092

Di Donna, A., Marco, B., & Tony, A. (2017). Energy Geostructures: Analysis from research and systems installed around the World. *Proc. In DFI 2017: 42nd Annual Conference on Deep Foundations, USA*. DFI.

Eskilson, P. (1987). *Thermal Analysis of Heat Extraction* (L. I. Q. 87 Grahns Boktryckeri AB (ed.)). University of Lund, Sweden.

Ferrantelli, A., Fadejev, J., & Kurnitski, J. (2020). *A tabulated sizing method for the early stage design of geothermal energy piles including thermal storage*.

Fossa, M., & Rolando, D. (2014). Fully analytical finite line source solution for fast calculation of temperature response factors in geothermal heat pump borefield design. *Proc. Proceedings, IEA Heat Pump Conference, 12-16 May, Montreal (Québec) Canada*.

Fossa, Marco. (2011). A fast method for evaluating the performance of complex arrangements of borehole heat exchangers. *HVAC&R Research*, 17(6), 948–958. https://doi.org/10.1080/10789669.2011.599764

Fossa, Marco, Cauret, O., & Bernier, M. (2009). Comparing the thermal performance of ground heat exchangers of various lengths. *Proc. Proceedings from the 11th International Conference on Energy Storage, EFFSTOCK*.

Fossa, Marco, & Rolando, D. (2015). Improving the Ashrae method for vertical geothermal borefield design. *Energy and Buildings*, 93, 315–323. https://doi.org/https://doi.org/10.1016/j.enbuild.2015.02.008

Gaia Geothermal. (2016). *GLD Overview*. Retrieved in from http://www.gaiageo.com/products.html

Geo Connections. (2018). *Loop Link PRO*. Retrieved in from https://looplinkpro.com/features/

Hellström, G. (1991). Ground Heat Storage: Thermal Analyses of Duct Storage Systems. I.Theory (Issue v. 1). *Department of Mathematical Physics*. http://books.google.dk/books?id=Ox6lRwAACAAJ

Katsura, T., Nagano, K., & Takeda, S. (2008). Method of calculation of the ground temperature for multiple ground heat exchangers. *Applied Thermal Engineering*, 28(14–15), 1995–2004. https://doi.org/http://dx.doi.org/10.1016/j.applthermaleng.2007.12.013

Laloui, L., & Di Donna, A. (2013). *Energy Geostructures: Innovation in Underground Engineering*. John Wiley & Sons, Inc.

Laloui, L., & Rotta Loria, A. F. (2018). *Energy geostructures analysis and design. Intensive course at EPFL Lausanne*.

Lee, S., Park, S., Won, J., & Choi, H. (2021). Influential factors on thermal performance of energy slabs equipped with an insulation layer. *Renewable Energy*, 174, 823–834. https://doi.org/https://doi.org/10.1016/j.renene.2021.04.090

Loveridge, F. (2012). The thermal performance of foundation piles used as heat exchangers in ground energy systems. In *Faculty of Engineering and the Environment: Vol. PhD Thesis*. University of Southampton. http://eprints.soton.ac.uk/348910/

Loveridge, Fleur, McCartney, J. S., Narsilio, G. A., & Sanchez, M. (2020). Energy geostructures: A review of analysis approaches, in situ testing and model scale experiments. *Geomechanics for Energy and the Environment*, 22, 100173. https://doi.org/10.1016/J.GETE.2019.100173

Loveridge, Fleur, & Powrie, W. (2013). Temperature response functions (G-functions) for single pile heat exchangers. *Energy*, 57(0), 554–564. https://doi.org/http://dx.doi.org/10.1016/j.energy.2013.04.060

Loveridge, Fleur, & Powrie, W. (2014). G-Functions for multiple interacting pile heat exchangers. *Energy*, 64(0), 747–757. https://doi.org/http://dx.doi.org/10.1016/j.energy.2013.11.014

Makasis, N., Narsilio, G. A., & Bidarmaghz, A. (2018). A machine learning approach to energy pile design. *Computers and Geotechnics*, 97, 189–203. https://doi.org/10.1016/J.COMPGEO.2018.01.011

Monzó, P. (2018). *Modelling and monitoring thermal response of the ground in borehole fields*. KTH Royal Institute of Technology. https://www.diva-portal.org/smash/get/diva2:1178493/FULLTEXT01.pdf

Pahud, D. (1999). PILESIM - LASEN. Simulation Tool for Heating/Cooling Systems with Heat Exchanger Piles or Borehole Heat Exchangers. User Manual. http://repository.supsi.ch/id/eprint/3047

Pahud, D., & Hubbuch, M. (2007). Measured thermal performances of the energy pile system of the Dock Midfield at Zürich Airport. *Proc. Proceedings European geothermal congress*.

Philippe, M., Michel Bernier PhD, Pe., & Marchio, D. (2010). Sizing calculation spreadsheet: Vertical geothermal borefields. *Ashrae Journal*, 52(7), 20.

SIA. (2005). *Utilisation de la chaleur du sol par des ouvrages de fondation et de soutènement en béton: guide pour la coneption, la réalisation et la maintenance*. SIA, Société suisse des ingénieurs et des architectes. http://books.google.dk/books?id=Ki

Spitler, J D, & Bernier, M. (2016). 2 - Vertical borehole ground heat exchanger design methods A2 - Rees, Simon J. In *Advances in Ground-Source Heat Pump Systems* (pp. 29–61). Woodhead Publishing. https://doi.org/http://dx.doi.org/10.1016/B978-0-08-100311-4.00002-9

Spitler, Jeffrey D. (2000). GLHEPRO-A design tool for commercial building ground loop heat exchangers. *Proc. Proceedings of the fourth international heat pumps in cold climates conference*. Citeseer.

Vieira, A., Alberdi-Pagola, M., Christodoulides, P., Javed, S., Loveridge, F., Nguyen, F., Cecinato, F., Maranha, J., Florides, G., Prodan, I., Lysebetten, G. Van, Ramalho, E., Salciarini, D., Georgiev, A., Rosin-Paumier, S., Popov, R., Lenart, S., Poulsen, S. E., & Radioti, G. (2017). Characterisation of Ground Thermal and Thermo-Mechanical Behaviour for Shallow Geothermal Energy Applications. In *Energies* (Vol. 10, Issue 12). https://doi.org/10.3390/en10122044

Appendices

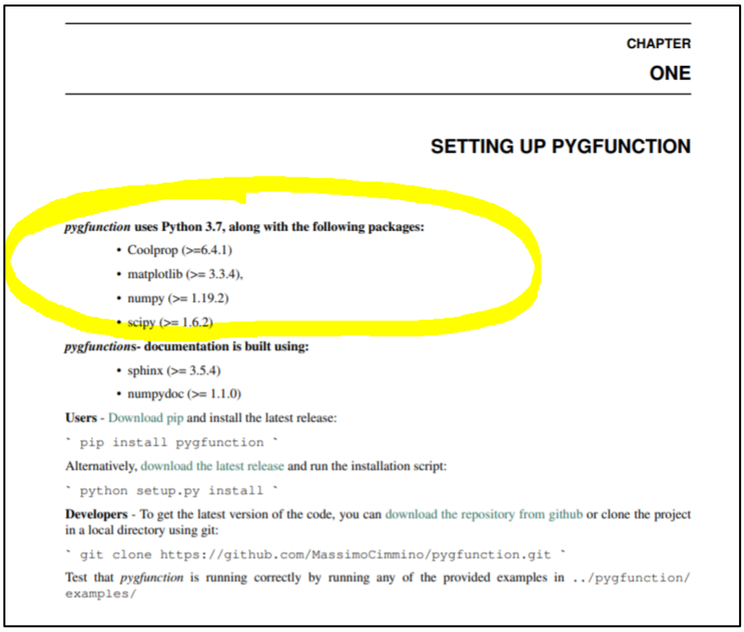
A.1 “pygfunction” installation in Anaconda & Spyder

This appendix describes how to install “pygfunction” package in Spyder. The documentation can be found in:

https://pypi.org/project/pygfunction/

https://github.com/MassimoCimmino/pygfunction/releases (M. Cimmino, 2018)

It is important that the requirements indicated in the documentation are followed:



CHAPTER

ONE

SETTING UP PYGFUNCTION

***pygfunction* uses Python 3.7, along with the following packages:**

- Coolprop (>=6.4.1)
- matplotlib (>= 3.3.4),
- numpy (>= 1.19.2)
- scipy (>= 1.6.2)

***pygfunctions*- documentation is built using:**

- sphinx (>= 3.5.4)
- numpydoc (>= 1.1.0)

Users - Download pip and install the latest release:

` pip install pygfunction `

Alternatively, download the latest release and run the installation script:

` python setup.py install `

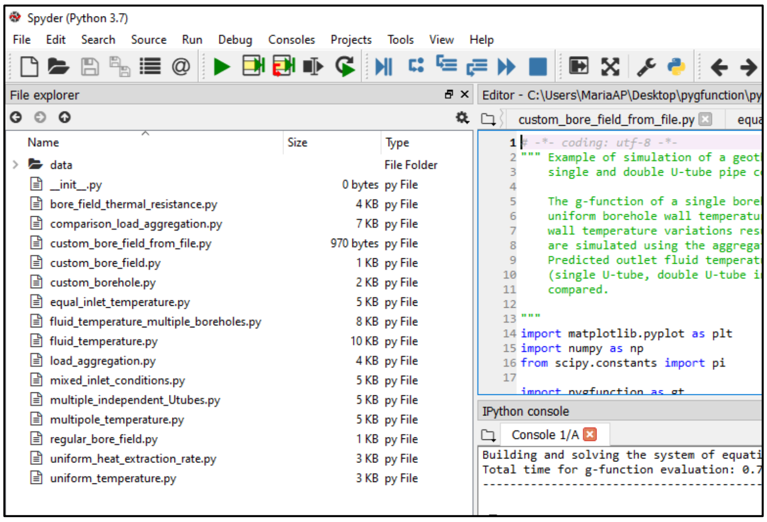
Developers - To get the latest version of the code, you can download the repository from github or clone the project in a local directory using git:

` git clone https://github.com/MassimoCimmino/pygfunction.git `

Test that *pygfunction* is running correctly by running any of the provided examples in `../pygfunction/examples/`

Create a new conda environment. For example, it could be “Interreg2” where Python 3.7 is established. “pygfunction” uses CoolProp package which does not work with Python 3.9.

Make sure that Spyder is installed in the new Interreg2 environment. It is important that Spyder works with Python 3.7.



Name	Size	Type
data		File Folder
__init__.py	0 bytes	py File
bore_field_thermal_resistance.py	4 KB	py File
comparison_load_aggregation.py	7 KB	py File
custom_bore_field_from_file.py	970 bytes	py File
custom_bore_field.py	1 KB	py File
custom_borehole.py	2 KB	py File
equal_inlet_temperature.py	5 KB	py File
fluid_temperature_multiple_boreholes.py	8 KB	py File
fluid_temperature.py	10 KB	py File
load_aggregation.py	4 KB	py File
mixed_inlet_conditions.py	5 KB	py File
multiple_independent_Utubes.py	5 KB	py File
multipole_temperature.py	5 KB	py File
regular_bore_field.py	1 KB	py File
uniform_heat_extraction_rate.py	3 KB	py File
uniform_temperature.py	3 KB	py File

```
# -*- coding: utf-8 -*-
""" Example of simulation of a geot
    single and double U-tube pipe c

    The g-function of a single bore
    uniform borehole wall temperatu
    wall temperature variations res
    are simulated using the aggrega
    Predicted outlet fluid temperat
    (single U-tube, double U-tube i
    compared.

"""
import matplotlib.pyplot as plt
import numpy as np
from scipy.constants import pi

import pygfunction as gt
```

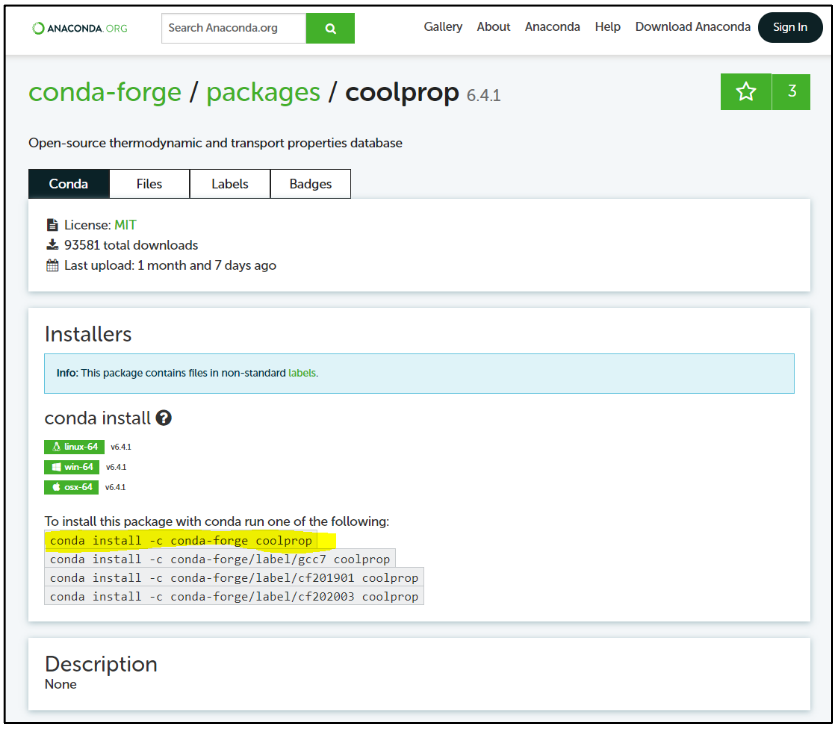
```
Building and solving the system of equati
Total time for g-function evaluation: 0.7
-----------------------------------------
```

python -m pip install --user pygfunction

>> conda install -c anaconda pip

Make sure the CoolProp package is installed as here: https://anaconda.org/conda-forge/coolprop

(This app explains only the way to install it from the conda prompt. There can be more options)



conda-forge / packages / coolprop 6.4.1

Open-source thermodynamic and transport properties database

License: MIT
93581 total downloads
Last upload: 1 month and 7 days ago

Installers

Info: This package contains files in non-standard labels.

conda install

linux-64 v6.4.1
win-64 v6.4.1
osx-64 v6.4.1

To install this package with conda run one of the following:

```
conda install -c conda-forge coolprop
conda install -c conda-forge/label/gcc7 coolprop
conda install -c conda-forge/label/cf201901 coolprop
conda install -c conda-forge/label/cf202003 coolprop
```

Description
None

We can choose to install the package through the conda prompt or through Spyder. For the prompt:

>> conda install -c anaconda pip

>> python -m pip install --user pygfunction