Chapter 3
OGS Project: Simulating Heat Transport Model with BHEs

3.1 Download and Compile the Source Code

Since OpenGeoSys is an open-source project, users can download the source code from the following website and build the binary executable file by themselves.

https://github.com/ufz/ogs5

For different platforms, i.e. Windows, Mac or Linux, the general procedure of building an OGS executable and running a model simulation would be very similar. Here in this chapter, such process will be demonstrated based on a Windows operation system. It will be shown step by step, how to build the source code and construct a simple model with one borehole heat exchanger in the middle of the model domain.

3.1.1 Download the Source Code

Assuming the Git command line interface has already been installed on the system, the OGS source code can be obtained by typing in the command line prompt the following content.

Listing 3.1 Downloading the source code with Git

```
C:\haibing_working\ogs>git clone https://github.com/ufz/ogs5.git
```

Or, if one prefers a graphical interface, it is recommend to use SourceTree on the Windows platform. After a fresh installation of the software SourceTree, the following interface will appear (Fig. 3.1). By clicking the button Clone/New in the upper-left corner, one will be asked to give the location of repository. You may use the Github link provided above, or first fork from the above repository and clone

H. Shao et al., *Geoenergy Modeling II*, SpringerBriefs in Energy,
DOI 10.1007/978-3-319-45057-5_3

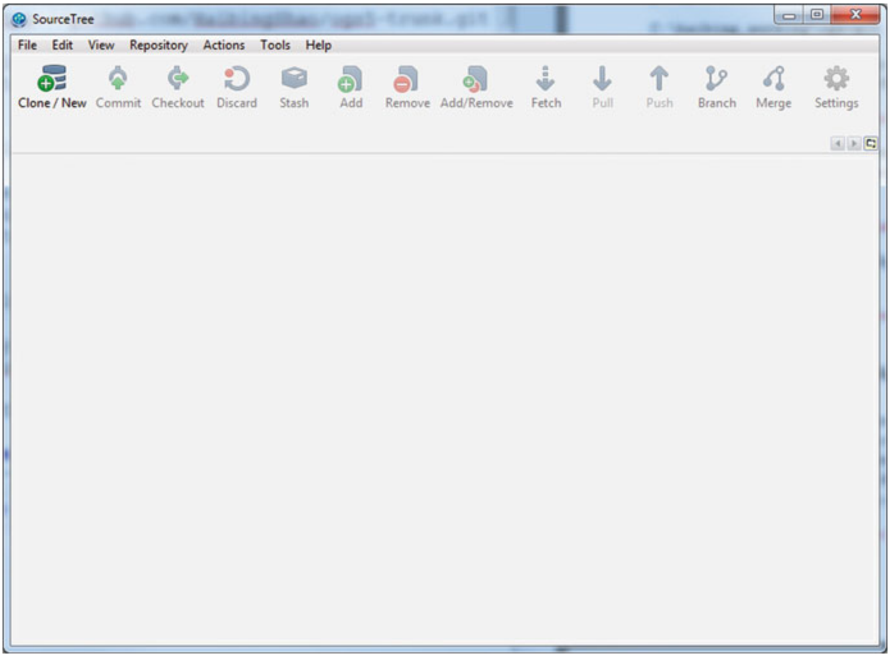


Fig. 3.1 SourceTree window as in the initial stage

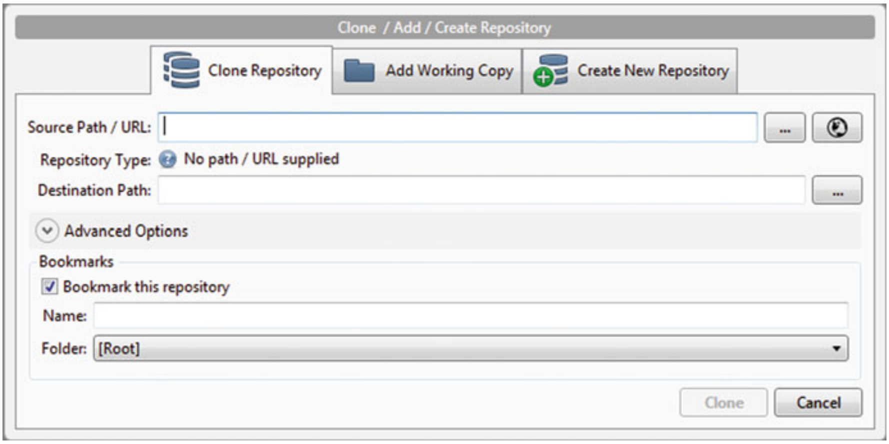


Fig. 3.2 SourceTree dialog asking for the location of the repository

from your own repository on Github (Fig. 3.2). After the code has been successfully cloned to a local drive, one can see all the history of code development in SourceTree as shown in Fig. 3.3.

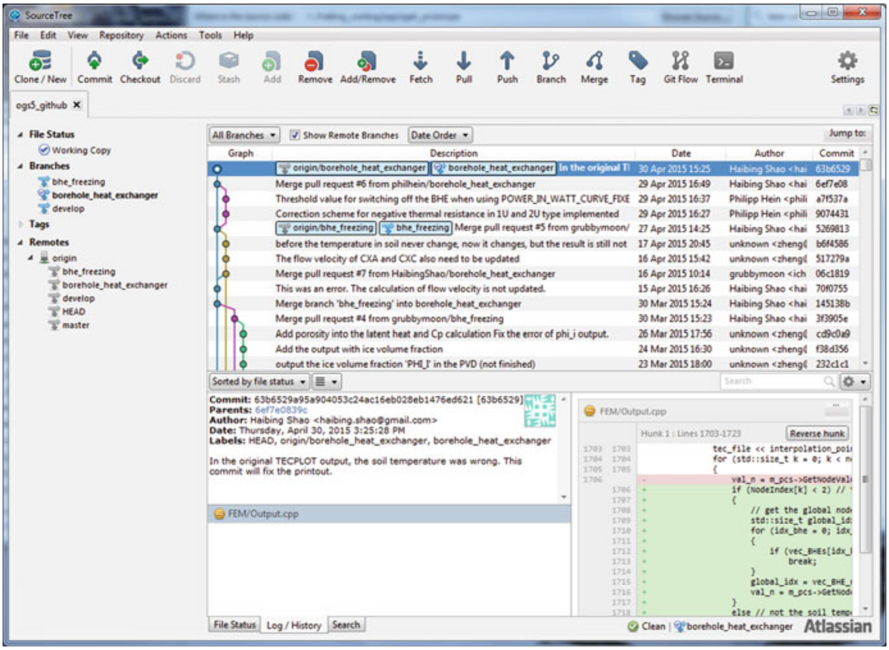


Fig. 3.3 SourceTree window with detailed history of a repository

3.1.2 Using CMake to Configure the Building Project

Before the compilation of the source code, the software CMake needs to be employed to generate the configuration and makefiles which are specific to the building environment. Here the CMake version 2.8.12.2 is employed for demonstration. In Fig. 3.4, CMake GUI was freshly started. First, one needs to define two paths in the CMake GUI. The first one is the folder where the source code of OGS is located. The second path refers to the folder where the makefiles will be generated. After clicking on the “Configure” button, CMake will ask several questions, depending on different types of operating system and the compiling tools. In this example, the “Visual Studio 2013 x86” option was chosen. Once the configuration has finished, the build options will be shown in the CMake GUI. To build the OpenGeoSys code with BHE features, one only needs to choose the option `OGS_FEM`. By clicking on the “Generate” button, CMake will prepare all makefiles in the build folder (Fig. 3.5).

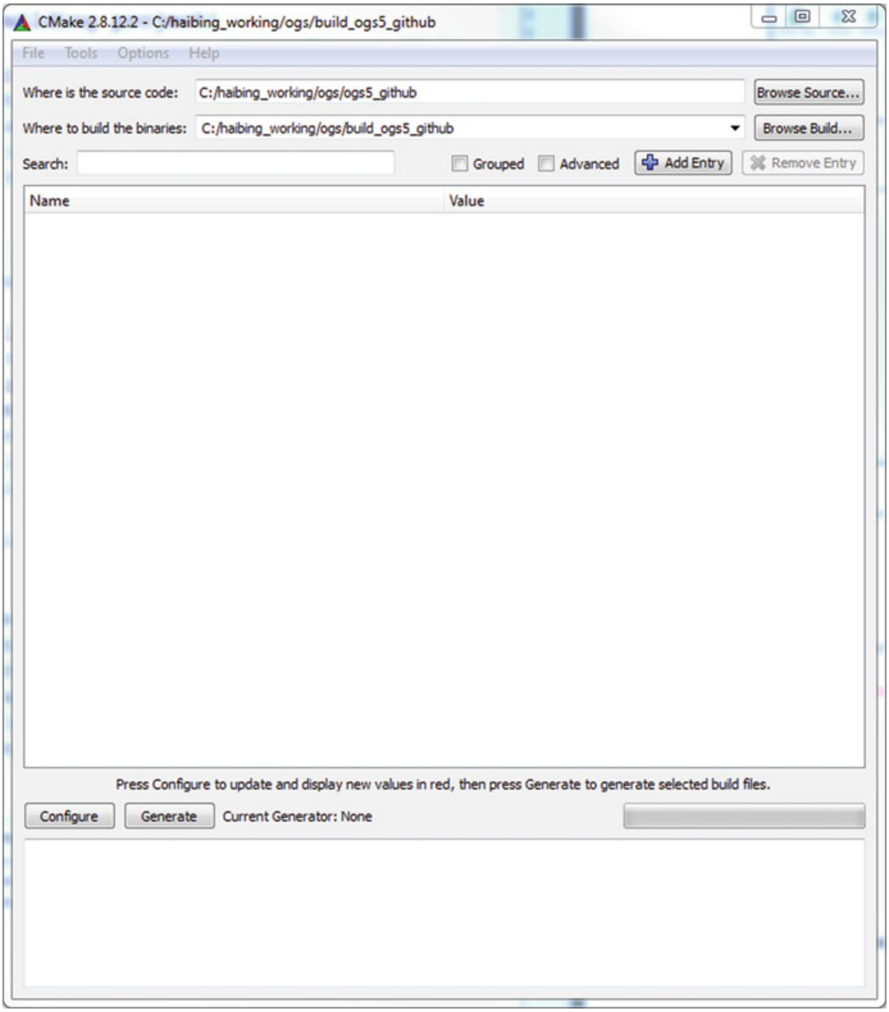


Fig. 3.4 CMake interface of configuring the build information

3.1.3 Compiling the Code

As the author is mainly developing the code with Microsoft Visual Studio, the building process will be demonstrated with the same software. Provided the configuration was accomplished by CMake successfully in the previous step, there will be a file named with “OGS.sln” in the build folder. By opening this Visual Studio solution

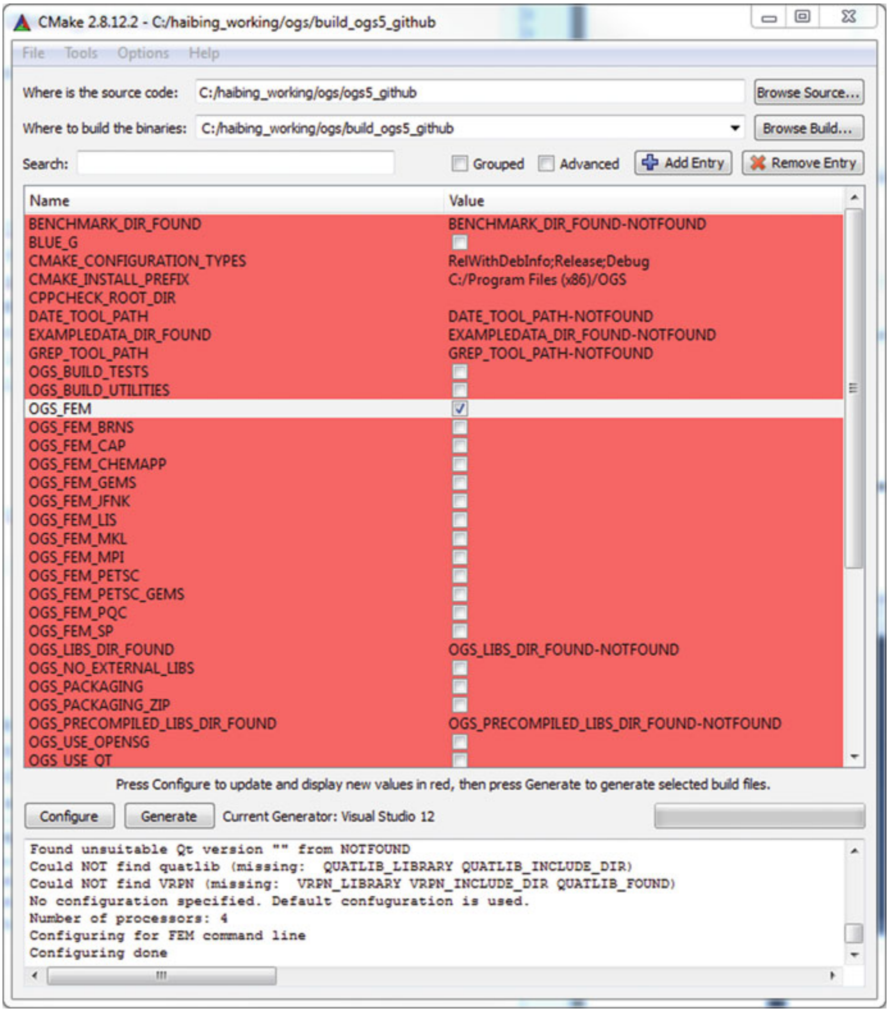


Fig. 3.5 CMake interface showing different building options

file, the source code will be loaded into the development environment along with all the building configurations (Fig. 3.6). To build the source code, just choose from the menu "BUILD", and then click on the first option "Build Solution". It takes a couple of minutes to run the full building process for the first time. After the building is completed, an executable file "ogs.exe" can be found under the "bin" folder and then "Debug" or "Release" folder, depending on which building mode has been adopted.

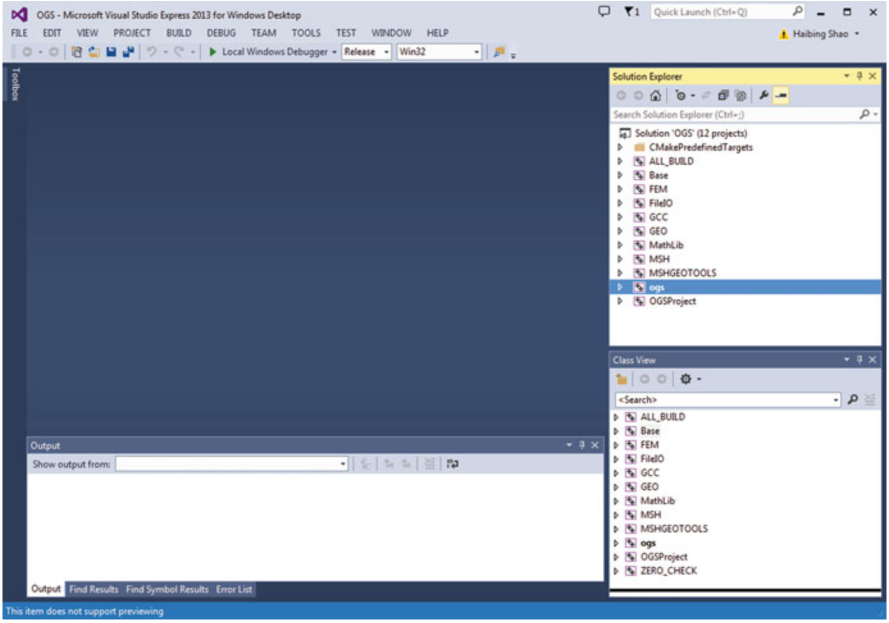


Fig. 3.6 Visual Studio interface after opening the OpenGeoSys solution file

3.2 Define Heat Transport Process with BHEs

In the last section, the OGS code was successfully compiled and an ogs.exe executable file has been built. In this section, a modelling project will be established to simulate the heat transport process with borehole heat exchangers.

3.2.1 Process Definition

Originally, the heat transport simulation in an OpenGeoSys project is performed by defining the process as `HEAT_TRANSPORT`. To include the interaction with BHEs, a new process has been introduced and named as "`HEAT_TRANSPORT_BHE`". The model input files bear the name "project_name.ext_name". The "project_name" is a unique string defined by the user to identify a project. The "ext_name" are pre-defined extensions which refers to a particular type of input configuration. In the following, a PCS file is first introduced, with one `GROUNDWATER_FLOW` and one `HEAT_TRANSPORT_BHE` process defined in it. If the project is named as "bhe_test", then the PCS file should be named as "bhe_test.pcs". Its content is shown in the following text box.

Listing 3.2 PCS File Definition including Interaction with Borehole Heat Exchangers

```
#PROCESS
$PCS_TYPE
  GROUNDWATER_FLOW
$DEACTIVATED_SUBDOMAIN
  1
  1
#PROCESS
 $PCS_TYPE
   HEAT_TRANSPORT_BHE
 $PRIMARY_VARIABLE
   TEMPERATURE_SOIL
#STOP
```

3.2.2 *Deactivated Sub-domains*

In the above PCS file, some readers might have already noticed that there are two numbers given under the key word `$DEACTIVATED_SUBDOMAIN`. The first number "1" on line #7 means there is one sub-domain deactivated for the `GROUNDWATER_FLOW` process, and the second number "1" on line #8 identifies the index of this deactivated domain. So why does the sub-domain "1" need to be turned off? This is because the sub-domain "0" in this project is referring to the soil domain, while the sub-domain "1" is the borehole heat exchanger compartment. Since the BHE is grouted and impermeable, it is not necessary to calculate groundwater flow through a BHE. Therefore its representative sub-domain is deactivated.

3.2.3 *Primary Variables*

In Sects. 2.1 and 2.2, it has been introduced that there are multiple primary variables applied in the BHE simulation. In the soil sub-domain primary variable is the soil temperature, while on the BHE they are the temperatures of inlet outlet pipes and the surrounding grout zones. The key words used for these processes, are summarized in Table 3.1. In Sect. 3.8, when the output is specified, these key words will be used.

3.3 Geometry of BHEs

Listing 3.3 Geometry Definition in the GLI File of an OpenGeoSys Project

```
#POINTS
0   0.0 0.0   18.32 $NAME POINT0
1   1.8 0.0   18.32 $NAME POINT1
2   1.8 1.8   18.32 $NAME POINT2
```

Table 3.1 Key words used in OGS BHE project for different primary variables

Symbols	Key words	Meaning
T_s	TEMPERATURE_SOIL	Soil temperature
T_{i1}	TEMPERATURE_IN_1	Inflow temperature (1U, CXC, CXA)
T_{i2}	TEMPERATURE_IN_2	Inflow temperature (2U)
T_{o1}	TEMPERATURE_OUT_1	Outflow temperature (1U, CXC, CXA)
T_{o2}	TEMPERATURE_OUT_2	Outflow temperature (2U)
T_{g1}	TEMPERATURE_G_1	Temperature of grout zone 1
T_{g2}	TEMPERATURE_G_2	Temperature of grout zone 2
T_{g3}	TEMPERATURE_G_3	Temperature of grout zone 3
T_{g4}	TEMPERATURE_G_4	Temperature of grout zone 4

```
3  0.0 1.8  18.32 $NAME POINT3
4  0.9 0.9  18.32 $NAME POINT4
5  0.0 0.0  0.0   $NAME POINT5
6  1.8 0.0  0.0   $NAME POINT6
7  1.8 1.8  0.0   $NAME POINT7
8  0.0 1.8  0.0   $NAME POINT8
9  0.9 0.9  0.0   $NAME POINT9
10 1.14 0.9  18.32 $NAME POINT10
11 1.14 0.9  0.0   $NAME POINT11
12 1.34 0.9  18.32 $NAME POINT12
13 1.34 0.9  0.0   $NAME POINT13
14 1.55 0.9  18.32 $NAME POINT14
15 1.55 0.9  0.0   $NAME POINT15
16 1.75 0.9  18.32 $NAME POINT16
17 1.75 0.9  0.0   $NAME POINT17
#POLYLINE
$NAME
BHE_1
$POINTS
4
9
#STOP
```

As shown in the GLI file above, “BHE_1” is referring to a polyline starting from point #4 and ending until point #9. To define different BHEs, each BHE in the model has to be given a different polyline in the geometry definition. The geometry names will be used afterwards in the MMP and OUT file as a reference to differentiate the BHEs.

3.4 Mesh of BHEs

In Sect. 2.3.1, it has been already introduced that the BHEs are treated in the OGS model as a second domain. Generally, the soil matrix is meshed with 3D prism elements. In comparison to standard mesh file, the location of all mesh nodes remains the same, while additional 1D elements are added at the end of the element section, to represent the BHEs.

Listing 3.4 The Element Section in MSH File

```
$ELEMENTS
155062
0 0 pris 1673 1582 1671 598 507 596
...
14650 0 pris 7627 7614 7541 6552 6539 6466
14651 1 pris 9198 9107 9196 8123 8032 8121
...
23022 1 pris 11927 11914 11841 10852 10839 10766
23023 2 pris 13498 13407 13496 12423 12332 12421
...
56510 2 pris 29127 29114 29041 28052 28039 27966
56511 3 pris 30698 30607 30696 29623 29532 29621
...
154881 3 pris 79652 79639 79566 78577 78564 78491
154882 4 line 4 1079
...
154926 4 line 47304 48379
154927 5 line 5 1080
...
154971 5 line 47305 48380
154972 6 line 6 1081
...
155016 6 line 47306 48381
155017 7 line 7 1082
...
155061 7 line 47307 48382
#STOP
```

In the mesh file, different BHEs are marked with different material group indices. Taking the above mesh file as an example, the first number in each row denotes the index of the element. After that comes the index of the material group. In this project, there are all together eight material groups, with the index from 0 to 7. The material group #0, #1, #2 and #3 refers to the four soil layers in the simulation domain. That is why they are meshed with 3D prism elements. For the material group #4, #5, #6 and #7, each of them represents a BHE, which is meshed with 1D line elements. Since different BHEs might have different configurations, such as the depth, U-tube diameters, and flow rates etc., these BHE parameters are given as part of the material group definition in the MMP file. In Chap. 4, introduction will be given regarding how to use a meshing tool to generate the mesh file.

3.5 Parameters of BHEs

The parameters of the borehole heat exchangers are listed in the MMP file. In the following text box, an example was given. For each BHE, a unique MMP record needs to be given, starting with the key word “#MEDIUM_PROPERTIES”. Under the key word “$GEO_TYPE”, the corresponding polyline was given, identifying the location of this BHE. Following the key word “$BOREHOLE_HEAT_EXCHANGER”, more specific information was defined, such as the length of the BHE, borehole diameter, refrigerant flow rate etc. Most of the key words applied here are self-explanatory. A more detailed definition is listed in Table 3.2.

Table 3.2 Parameters of BHE configuration available in the MMP file

Key words	Value to fill	Unit	Default value	Remarks
BHE_TYPE	BHE_TYPE_1U BHE_TYPE_2U BHE_TYPE_CXA BHE_TYPE_CXC	–		Specify the type of BHE
BHE_BOUNDARY_TYPE	FIXED_INFLOW_TEMP FIXED_INFLOW_TEMP_CURVE POWER_IN_WATT POWER_IN_WATT_CURVE_FIXED_DT POWER_IN_WATT_CURVE_FIXED_FLOW_RATE FIXED_TEMP_DIFF	–		Different boundary conditions for the BHE
BHE_POWER_IN_WATT_VALUE	Double number	W		A fixed power value Positive means heating the BHE, Negative means cooling
BHE_POWER_IN_WATT_CURVE_IDX	Integer number	–		Index of curve in the RFD file
BHE_DELTA_T_VALUE	Double number	K		Only when the boundary type FIXED_TEMP_DIFF is chosen
BHE_SWITCH_OFF_THRESHOLD	Double number	K		
BHE_LENGTH	Double number	m		Length of the BHE
BHE_DIAMETER	Double number	m		Diameter of the borehole
BHE_REFRIGERANT_FLOW_RATE	Double number	m^3/s		Flow rate of circulating refrigerant inside the pipeline of the BHE
BHE_INNER_RADIUS_PIPE	Double number	m		Inner radius of the pipe
BHE_OUTER_RADIUS_PIPE	Double number	m		Outer radius of the pipe
BHE_PIPE_IN_WALL_THICKNESS	Double number	m		Inlet pipe wall thickness
BHE_PIPE_OUT_WALL_THICKNESS	Double number	m		Outlet pipe wall thickness
BHE_FLUID_TYPE	Integer number	m		Index of fluid defined in the MFP file

Listing 3.5 Definition of BHE parameters in MMP File

```
; properties of BHE 1
#MEDIUM_PROPERTIES
 $GEO_TYPE
   POLYLINE BHE_1
 $BOREHOLE_HEAT_EXCHANGER
   BHE_TYPE
     BHE_TYPE_1U
   BHE_BOUNDARY_TYPE
     POWER_IN_WATT_CURVE_FIXED_FLOW_RATE  ;
   BHE_POWER_IN_WATT_CURVE_IDX
     1
   BHE_LENGTH
     46
   BHE_DIAMETER
     0.15
   BHE_REFRIGERANT_FLOW_RATE
     9.17E-05
   BHE_INNER_RADIUS_PIPE
     0.0131
......
```

One parameter that needs further explanation is the boundary condition that will be imposed on a BHE. In most cases, the inflow temperature of the BHE is controlled by the operation logic of the heat pump, and subsequently by the thermal load from the building. Therefore, several different types of BHE boundary conditions have been provided in the MMP files.

- FIXED_INFLOW_TEMP
  This is the simplest case, where the BHE inflow temperature is a constant over the simulation period. Such kind of boundary condition is rarely used for real scenario analysis, but for testing and benchmark purposes it is kept in the configuration.
- FIXED_INFLOW_TEMP_CURVE
  With this type of boundary condition, the BHE inflow temperature is specified according to a time dependent curve, which is defined in the RFD file. An example of time dependent curve can be found in one of the benchmark cases (Sect. 5.2).
- FIXED_TEMP_DIFF
  Some heat pump adopt an operation logic, which impose a fixed temperature difference between the inflow and outflow from the BHE. When this type of boundary condition is specified, the numerical model will first check the outflow temperature, and then calculate the inflow temperature by adding this ΔT value.
- POWER_IN_WATT
  This type of boundary configuration will specify the amount of power withdrawn or injected through the BHE. In the former case, there will be a negative value, and in the latter one a positive number. Through the simulation, the program will divide this power value by the product of fluid heat capacity, fluid density and the flow rate. The resultant ΔT value will then be added on the outflow temperature, through which the inflow temperature is determined. Such calculation will be performed before each iteration of the linear equation solution.

- POWER_IN_WATT_CURVE_FIXED_DT
  In this scenario, the BHE thermal load is specified according to a predefined curve in the RFD file. Meanwhile, a fixed ΔT values will be maintained, i.e. the flow rate will be dynamically calculated based on the thermal load, the circulating fluid properties, and the given ΔT value. If the resultant flow rate is below a certain threshold (by default $1.0 \times 10^{-6}\,\mathrm{m}^3/\mathrm{s}$, the program will assume that the heat pump and fluid circulation is switched off.
- POWER_IN_WATT_CURVE_FIXED_FLOW_RATE
  Different from the previous configuration, this type of boundary will maintain a fixed flow rate instead of ΔT. In this case the ΔT value will be dynamically calculated using the same relationship, while the flow rate is kept the same.
- BHE_BOUND_BUILDING_POWER_IN_WATT_CURVE_FIXED_DT
  and
  BHE_BOUND_BUILDING_POWER_IN_WATT_CURVE_FIXED_
  FLOW_RATE
  The additional feature in these two types of boundary is the inclusion of heat pump efficiency. Conventionally, this efficiency value is quantified by the coefficient of performance (COP) Casasso and Sethi (2014)

$$COP = \frac{\dot{Q}}{W} \tag{3.1}$$

where $\dot{Q}$ is the amount of thermal power required by the building, and W is the electricity consumed by the heat pump. The COP can be determined by the temperature of circulating fluid at the BHE outlet, and the temperature required at the heating end [see Jaszczur and Śliwa (2013) and also Eq. (3.2)]. Although there are other factors influencing the heat pump COP, it is widely assumed that the COP is linearly dependent on the BHE outflow temperature. The same simplification can be found in e.g. Kahraman and Çelebi (2009), Casasso and Sethi (2014) and Sanner et al. (2003). The COP of a typical heat pump can be approximated by the following relationship,

$$COP = a + bT_{out} \tag{3.2}$$

where the parameters a and b is can be defined in the MMP file.

In reality, the thermal load of the BHE $\dot{Q}_{BHE}$ is not the same as the building heat demand $\dot{Q}_{Building}$ (see e.g. Casasso and Sethi 2014; Eicker and Vorschulze 2009; Speer 2005). To shift the heat from the ground to the building, the heat pump needs about 20–30 % of the energy in the form of electricity. This amount of heat must be subtracted from the thermal load.

$$\dot{Q}_{BHE} = \dot{Q}_{Building} \frac{COP - 1}{COP} \tag{3.3}$$

This effect will be explicitly considered by these two boundary conditions. With these two configurations, the building thermal load is specified. During the model simulation, the COP of the heat pump will be dynamically calculated by OGS, and the amount of BHE thermal load will be updated accordingly.

3.6 Initial Conditions for the BHE

In the IC file, initial temperatures on different compartments of the BHE have to be given, together with temperatures of the soil at the beginning of the simulation. The following example shows that the initial temperature of the soil, of the inlet and outlet pipeline are all set to be 22 °C. Notice that the initial condition must be imposed also on the two grout zones surrounding the pipelines.

Listing 3.6 The Initial Condition Configuration

```
#INITIAL_CONDITION
 $PCS_TYPE
  HEAT_TRANSPORT_BHE
 $PRIMARY_VARIABLE
  TEMPERATURE_SOIL
 $GEO_TYPE
  DOMAIN
 $DIS_TYPE
  CONSTANT  22.0

#INITIAL_CONDITION
 $PCS_TYPE
  HEAT_TRANSPORT_BHE
 $PRIMARY_VARIABLE
  TEMPERATURE_IN_1
 $GEO_TYPE
  POLYLINE BHE_1
 $DIS_TYPE
  CONSTANT  22.0

#INITIAL_CONDITION
 $PCS_TYPE
  HEAT_TRANSPORT_BHE
 $PRIMARY_VARIABLE
  TEMPERATURE_OUT_1
 $GEO_TYPE
  POLYLINE BHE_1
 $DIS_TYPE
  CONSTANT  22.0
...
```

It is very often that the shallow subsurface has a natural geothermal gradient. In this case, the initial temperature of the soil can be specified to gradually increase along with the depth. The following example shows how to define such a case. There are three values after the keyword GRADIENT. The first values is the reference depth. The second one is the temperature value at this depth, and the third one is the geothermal gradient in the z-direction. In this example, the soil temperature was specified to be 13.32 °C at -120 m, and has a gradient of 0.016 K m^{-1} over the depth.

Listing 3.7 Initial Condition with Geothermal Gradient

```
...
#INITIAL_CONDITION
 $PCS_TYPE
  HEAT_TRANSPORT_BHE
 $PRIMARY_VARIABLE
  TEMPERATURE_SOIL
 $GEO_TYPE
  DOMAIN
 $DIS_TYPE
  GRADIENT -120 13.32 0.016
...
```

3.7 Boundary Conditions for the BHE

In Sect. 3.5, the different types of BHE boundary conditions have already been discussed in detail. Besides these configurations, the user still needs to define in the BC file, where the boundary condition should be applied. The following text box shows an example. Here two locations have been specified. The first one was defined on the starting node of the BHE, namely on POINT4. At this location, the inflow temperature was imposed according to curve #1 defined in the RFD file (see Sect. 5.2 for an example). The second location is on POINT9, which is at the bottom of the BHE. This second location is necessary, because OGS will internally read how high the temperature is on the inflow pipe and impose this value on the outflow pipe. Therefore, the value imposed on POINT9 will not have any effect on the simulation result.

Listing 3.8 Boundary condition configuration in the BC file

```
...
#BOUNDARY_CONDITION
 $PCS_TYPE
  HEAT_TRANSPORT_BHE
 $PRIMARY_VARIABLE
  TEMPERATURE_IN_1
 $GEO_TYPE
  POINT POINT4
 $DIS_TYPE
  CONSTANT 1.0
 $TIM_TYPE
  CURVE 1

#BOUNDARY_CONDITION
 $PCS_TYPE
  HEAT_TRANSPORT_BHE
 $PRIMARY_VARIABLE
  TEMPERATURE_OUT_1
 $GEO_TYPE
  POINT POINT9
 $DIS_TYPE
  CONSTANT 5.0
...
```

3.8 Output of Temperatures

In the OUT file, it is configured which of the simulated temperature values are going to be recorded by OGS. As shown in the following example, two different output records are specified, each starting with the key word #OUTPUT. In the first one, the soil temperature over the entire domain is printed out in the PVD format. In the second one, the inlet, outlet temperature of the pipe, the two grout zones surrounding them, and also the soil temperature along the BHE is plotted in the TECPLOT format. Under the key word TIM_TYPE, the specification "STEPS 10" means that the simulation result will be printed once in every ten time steps. Both the PVD format and the TECPLOT format output files can be read by a text editor.

Listing 3.9 The Output Configuration

```
#OUTPUT
  $PCS_TYPE
    HEAT_TRANSPORT_BHE
  $NOD_VALUES
    TEMPERATURE_SOIL
  $GEO_TYPE
    DOMAIN
  $DAT_TYPE
    PVD
  $TIM_TYPE
    STEPS 10
#OUTPUT
  $PCS_TYPE
    HEAT_TRANSPORT_BHE
  $NOD_VALUES
    TEMPERATURE_IN_1_BHE_1
    TEMPERATURE_OUT_1_BHE_1
    TEMPERATURE_G_1_BHE_1
    TEMPERATURE_G_2_BHE_1
    TEMPERATURE_SOIL
  $GEO_TYPE
    POLYLINE BHE_1
  $DAT_TYPE
    TECPLOT
  $TIM_TYPE
    STEPS 10
#STOP
```

3.9 Running the OGS Model

There are several ways to start the simulation. In general, the OGS simulator can be started by calling the executable file ogs.exe. The easiest approach would be to run the simulation in the same folder where the input files are located. After copying the ogs.exe file into the project folder, one can double-click on the executable, then the following windows will appear on the screen (cf. Fig. 3.7). Within this window, one can enter the project name without the dot and any extensions. As the input files are

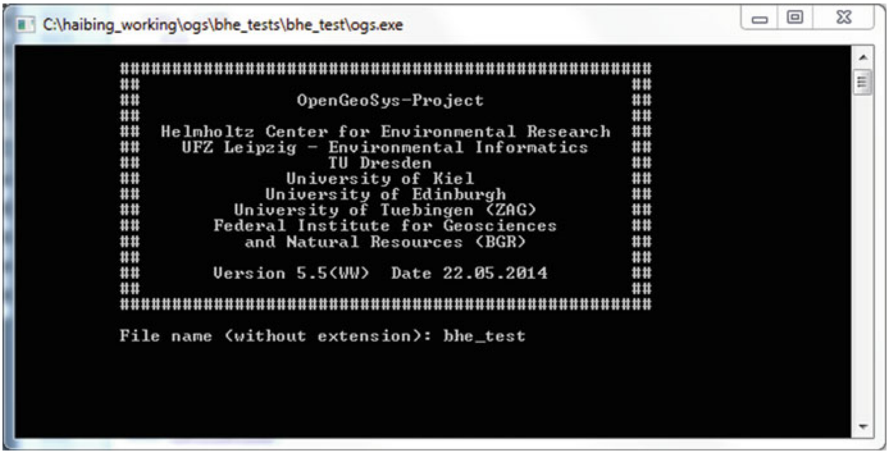


Fig. 3.7 Starting the simulation by calling the executable ogs.exe

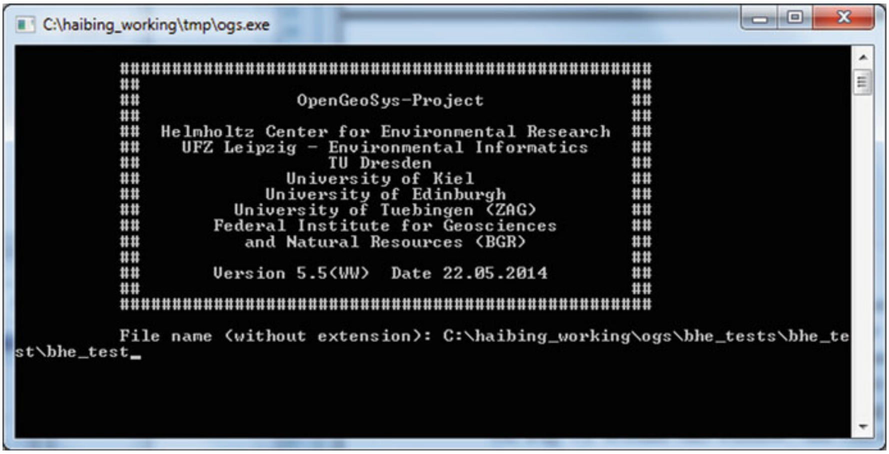


Fig. 3.8 Starting the simulation by calling the executable ogs.exe

name as "bhe_test.∗", entering "bhe_test" will be sufficient. After hitting the Enter key, the simulation will start.

An alternative approach is to have the executable placed at a different location, but supply the executable with the path to the project. As illustrated in Fig. 3.8, now ogs.exe is located under "C:\haibing\working\tmp". After launching ogs.exe, one can enter the project path "C:\haibing_working\ogs\ bhe_tests\bhe_test" to start the simulation. A easier way would be, to drag and drop one of the input files into the OGS command line prompt, and delete the extensions. As the OGS is designed to run on multiple platforms, it can not read in folder or file names with space in it. Please make sure that the path of the input files does not contain any space or special characters, otherwise OGS will not be able to find the right location.

While running the simulation, there is quiet a lot of logging information being printed on the screen. It includes which time step the simulation is in, how many nonlinear and linear iterations have been conducted, and how big is the numerical residual when solving the linear system. Such information is very helpful to the modeller, therefore it is recommended to save them in a log file. To do this, one could create an empty batch file, eg. named as "run_ogs.bat". Within it, just type in the following content.

Listing 3.10 The content of the batch file

```
ogs.exe bhe_test > result.txt
```

Here the symbol ">" will pipeline the screen output to the file "result.txt". By using this method, the user can open this text file and check the modelling progress while the simulation is still running.

3.10 Visualization of Temperature Evolution

As defined in the OUT file, there are two records in the output configuration, one for the soil temperatures, and the other for the inflow, outflow and grout temperatures on the BHEs (see the introduction in Sect. 3.8).

3.10.1 Visualization of Soil Temperatures

For the soil temperatures, they are recorded in the VTK format, and can be directly visualized by the software Paraview. As shown in Fig. 3.9, the result files are name as "bhe_test_HEAT_TRANSPORT_BHE*.*". The first part of the file name is the same as all the input files, while the second part is composed of the process that was simulated. For each of the *.vtu files, there is a number appending the file name, it reflects which time step this file belongs to. When visualizing the soil temperatures, one could directly load the *.pvd file, making paraview to read in all the printed result. Alternatively, one can also load a single *.vtu file, which only contains the soil temperature distribution at this time step.

Figure 3.10 demonstrates how the soil temperature will be influence by the BHE operation. In this example, the sandbox experiment from Beier et al. (2011) was reproduced (see Sect. 5.2 for more details). Since heat is injected through the U-tubes, the temperature at the center of the sandbox will gradually increase along time. This is reflected by red color at the center of the domain (Fig. 3.10).

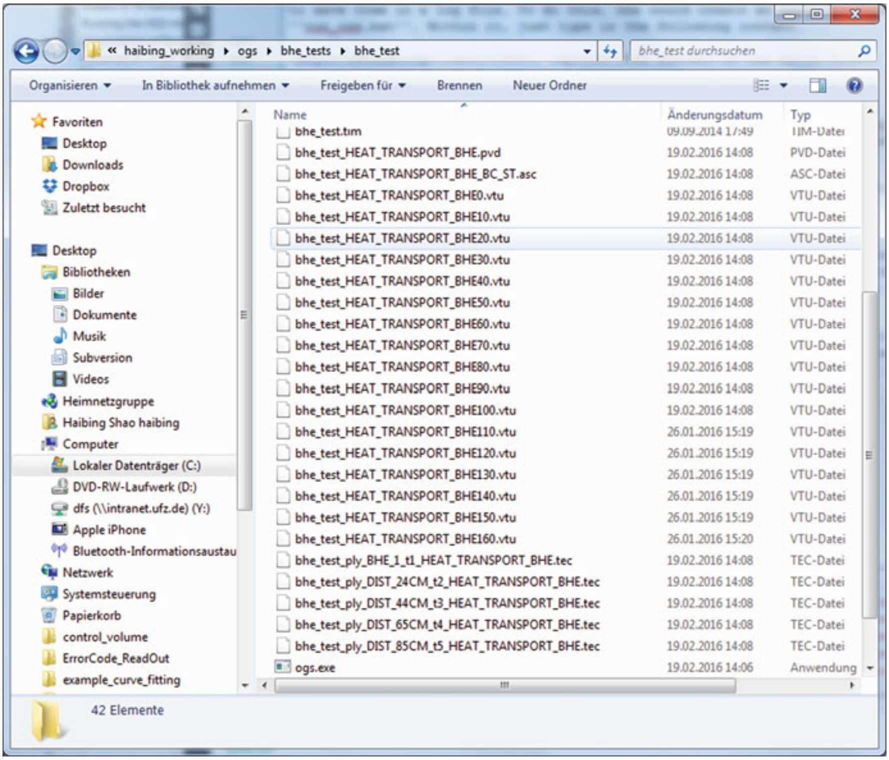


Fig. 3.9 Result files by a simulated OGS project

3.10.2 Visualization of BHE Temperatures

Different from the soil part, the information regarding temperatures inside the borehole heat exchanger is typically printed in the Tecplot file format. Figure 3.11 shows such an example. Here there are altogether six columns listed. From the left to the right, it is the distance from the top of the BHE, temperatures in the inflow and outflow pipeline, temperatures on the two grout zones, and finally BHE wall temperature. The order of the columns is actually defined in the *.out file. Notice that the pipeline temperature values at the bottom of the BHE, specifically on line #24 and #46, are kept the same. One can also import the data into a spreadsheet or plotting software, then the temperature distribution on each BHE can be visualized in a vertical profile.

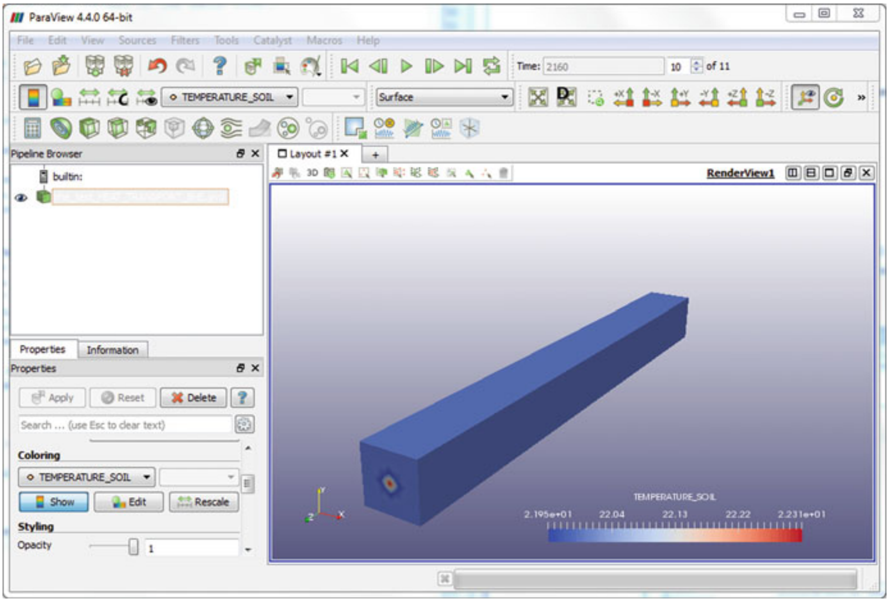
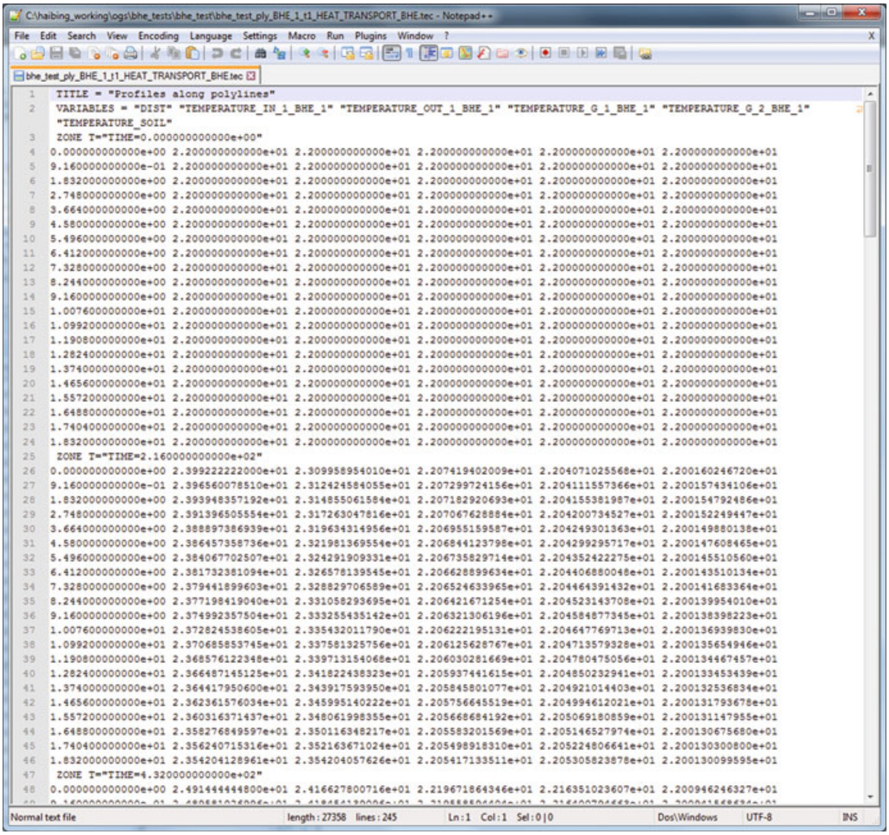


Fig. 3.10 Visualization effect of the simulated soil temperature distribution by the software Paraview




```
TITLE = "Profiles along polylines"
VARIABLES = "DIST" "TEMPERATURE_IN_1_BHE_1" "TEMPERATURE_OUT_1_BHE_1" "TEMPERATURE_G_1_BHE_1" "TEMPERATURE_G_2_BHE_1"
"TEMPERATURE_SOIL"
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0.000000000000e+00 2.200000000000e+01 2.200000000000e+01 2.200000000000e+01 2.200000000000e+01 2.200000000000e+01
9.160000000000e-01 2.200000000000e+01 2.200000000000e+01 2.200000000000e+01 2.200000000000e+01 2.200000000000e+01
1.832000000000e+00 2.200000000000e+01 2.200000000000e+01 2.200000000000e+01 2.200000000000e+01 2.200000000000e+01
2.748000000000e+00 2.200000000000e+01 2.200000000000e+01 2.200000000000e+01 2.200000000000e+01 2.200000000000e+01
3.664000000000e+00 2.200000000000e+01 2.200000000000e+01 2.200000000000e+01 2.200000000000e+01 2.200000000000e+01
4.580000000000e+00 2.200000000000e+01 2.200000000000e+01 2.200000000000e+01 2.200000000000e+01 2.200000000000e+01
5.496000000000e+00 2.200000000000e+01 2.200000000000e+01 2.200000000000e+01 2.200000000000e+01 2.200000000000e+01
6.412000000000e+00 2.200000000000e+01 2.200000000000e+01 2.200000000000e+01 2.200000000000e+01 2.200000000000e+01
7.328000000000e+00 2.200000000000e+01 2.200000000000e+01 2.200000000000e+01 2.200000000000e+01 2.200000000000e+01
8.244000000000e+00 2.200000000000e+01 2.200000000000e+01 2.200000000000e+01 2.200000000000e+01 2.200000000000e+01
9.160000000000e+00 2.200000000000e+01 2.200000000000e+01 2.200000000000e+01 2.200000000000e+01 2.200000000000e+01
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1.740400000000e+01 2.200000000000e+01 2.200000000000e+01 2.200000000000e+01 2.200000000000e+01 2.200000000000e+01
1.832000000000e+01 2.200000000000e+01 2.200000000000e+01 2.200000000000e+01 2.200000000000e+01 2.200000000000e+01
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1.832000000000e+00 2.393948357192e+01 2.314855061584e+01 2.207182920693e+01 2.204155381987e+01 2.200154792486e+01
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6.412000000000e+00 2.381732381094e+01 2.326578139545e+01 2.206628899634e+01 2.204406880048e+01 2.200143510134e+01
7.328000000000e+00 2.379441899603e+01 2.328829706589e+01 2.206524633965e+01 2.204464391432e+01 2.200141683364e+01
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9.160000000000e+00 2.374992357504e+01 2.333255435142e+01 2.206321306196e+01 2.204584877345e+01 2.200138398223e+01
1.007600000000e+01 2.372824538605e+01 2.335432011790e+01 2.206222195131e+01 2.204647769713e+01 2.200136939830e+01
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Fig. 3.11 Simulated temperature values printed in the Tecplot file format