

## **Review of manuscript:**

# **“LABORATORY EXPERIMENTAL INVESTIGATION OF HEAT TRANSPORT IN FRACTURED MEDIA”**

**By Claudia Cherubini et al.**

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## **General comments**

This paper presents an actual subject (heat transport in fractured media) with economical and ecological implications (geothermal energy plants as one of the renewable energies). The authors present an experiment which is very interesting and original due to their experimental apparatus and setup. The theory of the subject is clearly stated by the authors with a detailed and wide description.

The main objective of the paper is to study the mass and heat fluxes in a fractured media which behaviour is not well understood and it is an important topic for geothermal energy extraction. The authors use the explicit network model (ENM) to analyze the behaviour by means of several parameters shown in different figures (concentration and heat as a function of time, evolution of convective velocity, the dispersion coefficient and several time scales and non-dimensional numbers).

The authors of this work establish the basis to analyze the optimal conditions for thermal exchange in fractured media; they also deduce that the thermal dispersion dominates heat transport dynamics and the role of the rock-fracture size ratio.

The authors should explain better the applications of their conclusions at sections Results and Discussion and Conclusions. Explain how their results are important for industrial situations (energy plants) and if their conclusions establish any limitation to the use or to the characteristics of geothermal energy plants.

This paper should undergo a minor revision and some technical corrections before being considered for publication.

## **Specific comments**

### **Abstract**

- **Page 1, Lines 14-15.** You say: "One of the major limitations related to the choice of installing low enthalpy geothermal power plants regards the initial investment costs." Is it possible you add and describe more problems and limitations?

### **Introduction**

- **Page 5, Lines 123-138.** You mention several dilemmas. How does your study help to clarify these problems?
- **Page 5, Line 143.** What is the tortuosity factor?

### **Section "Theoretical background".**

#### **Subsection "Nonlinear flow"**

- **Page 7, Line 187.** What is the hydraulic head?

### **Section "Theoretical background".**

#### **Subsection "Heat transfer by water flow in single fractures"**

- **Page 8, Line 221.** Explain better the meaning of  $D_e$  and  $k_e$ .
- **Page 9, Line 243.** What is the function  $\theta_m$ ?
- **Page 10, Line 259.** Explain what is the residence time.
- **Page 11, Lines 288.** The Peclet number you define, is it not the ratio between dispersive ( $t_d$ ) to convective ( $t_u$ ) transport times?

### **Section "Theoretical background".**

#### **Subsection "Explicit network model"**

- **Page 12, Lines 311.** Introduce or describe the main characteristics of the ENM model.
- **Page 13, Lines 329 and 330.** Which is the subscript of the summation in equation (35) and line 330? The same applies to equation (38) and line 354 in page 14.

### **Section "Material and methods"**

#### **Subsection "Flow experiments"**

- **Page 15, Line 381.** Is the average hydraulic head the same that head loss?

### **Section "Material and methods"**

#### **Subsection "Solute and temperature tracer tests"**

- **Page 16, Line 394-395.** Describe what is the instantaneous source assumption and why you can use it.

## Section "Results and discussion"

### Subsection "Flow characteristics"

- **Page 16, Line 407.** Why have the linear and nonlinear terms been assumed equal?
- **Page 16. Line 410.** Explain better how to get the equation (42). Describe also what is the meaning of  $Q_0$  and  $R_i$  with  $i=1-9$  in a new line.
- **Page 16. Line 412.** Explain better how to get the equation (43).
- **Page 17. Line 417.** Which is the meaning and importance of the critical flow rate,  $Q_{crit}$ ?
- **Page 17. Lines 417-418.** Could you explain better why the critical flow rate,  $Q_{crit}$  can be determined in correspondence of  $Fo=1$  as the ratio between  $a$  and  $b$ ?

## Section "Results and discussion"

### Subsection "Fitting of breakthrough curves and interpretation of estimated model parameters"

- **Page 17. Lines 425 to 428.** Is there any adimensional number to do easier the comparison of these different experiments.
- **Page 17. Lines 430-431.** Why are the transport parameters  $u_f$ ,  $D_f$  and  $\alpha$  assumed equal for all branches?
- **Page 18. Line 445.** Why the characteristic length is equal to 0.601?
- **Page 19. Line 493.** Is the mean travel time the same magnitude that the mean residence time (Y-axis of Figure 8).
- **Page 21. Lines 543 to 547.** Which could be the practical use of the conclusions described in these lines?
- **Page 22. Line 558-559.** Could you explain how the gradient of  $T_m$  is evaluated according to Equation (16)?
- **Page 22. Lines 566 and 567.** Which are the implications of your conclusion that there is a solid thermal resistance which depends on the rock – fracture size ratio?

## Section "Conclusions"

- **Page 23. Lines 602 and 603.** Could you describe in more detail the optimal conditions for thermal exchange in a fracture network and your future research?

## Technical comments

- There is not section numbering. Number all sections and subsections as follows:
  - 1 Introduction
  - 2 .....
    - 2.1 .....
    - 2.2 .....
  - 3 .....
- *Be careful with the use of subscripts. For a given magnitude, sometimes you use subscripts and other not (for example,  $Da$ ). Revise the whole text.*

- You would write equations from (39) to (53) in a larger size.

## Abstract

- **Page 1, Lines 13.** Add or: "cooling of industrial processes, food drying systems *or* desalination".

## Introduction

- **Page 6.** Add a new paragraph at the end of the Introduction section to summarize your paper as follows: "*In section 1 we shows.....Section 2 describe....*".

## Section "Theoretical background".

### Subsection "Nonlinear flow"

- **Page 7, Line 186.** Add the meaning of the coefficients  $\mu$ ,  $u_f$ ,  $k$ ,  $\rho$  and  $p$ .
- **Page 7, Line 189.** You write: "The coefficients  $a$  (TL-1) and  $b$  (TL-2) represent...." I think that is not  $a$  and  $b$  but  $a'$  y  $b'$ .

## Section "Theoretical background".

### Subsection "Heat transfer by water flow in single fractures"

- **Page 8, Line 217.** In equation (8) you write  $C_m$  in capital letter but in equation (6) you write  $c_m$  in lower case letter. Are they the same coefficients,  $C_m$  and  $c_m$ , or are different? If they are the same, use the same notation (in capital letter or in lower case letter always). The same applies to the equations (10) and (12). The same applies to lines 247 and 251 of page 9 or in equation (14).
- **Page 9, Line 231.** If you define  $u_f$  before, in line 186 of page 7, you must eliminate it in line 231 of page 9.
- **Page 9, Line 244.** You write: "(-) the matrix porosity". What is the symbol (-)?
- **Page 9, Line 248.** You write: "function of time in Laplace space.". Eliminate the point and write something like "as follows".
- **Page 9, Line 250.** After this line, write another one to define the magnitudes  $s$ ,  $\nu$ ,  $L$ ,  $\beta$ ,  $A$  and  $B$ .
- **Page 9, Line 251 and Page 10, Line 252.** Write these two lines later and after equation (19).
- **Page 10, Lines 253 to 257.** Write these lines before and after equation (14) in line 250.
- **Page 10, Lines 255.** Equation (17) is:

$$A = \frac{\delta}{\sqrt{\theta D_e}}; \theta = \theta_m$$

Why not write

$$A = \frac{\delta}{\sqrt{\theta D_e}}; \theta = \theta_m$$

- **Page 10, Lines 258.** You write: "Furthermore on the basis of these analytical solutions the probability density function of the solute residence time (*PDF*)". Change this line as follows:

“Furthermore on the basis of these analytical solutions the probability density function (PDF) of the solute residence time.”

- **Page 11, Lines 271 and 274.** In equation (26) you write  $C_w$  in capital letter but in equation (23) you write  $c_w$  in lower case letter. Are they the same coefficients,  $C_w$  and  $c_w$ , or are different? If they are the same, use the same notation (in capital letter or in lower case letter always).
- **Page 11, Lines 278.** Eliminate the semicolon at the end of equation (25).
- **Page 11, Lines 279.** Rewrite equation (26):

$$A = \frac{\delta}{\sqrt{\theta D_e}}; \quad \theta = \frac{\rho_m C_m}{\rho_f C_f}, \quad D_e = \frac{k_e}{\rho_w C_w}$$

For example:  $A = \dots$  where  $\theta = \dots$  and  $D_e = \dots$

- **Page 12, Lines 294 to 298.** First, define Damköhler number and use equation (32). Second, write your line “Note that the inverse of  $t_e \dots$ ” and define  $\alpha$  with equation (31). Again, be careful with subscript: you write  $Da$  in equation (32) and  $D_a$  in line 296, 299, 302, 303. .... In equation (33), no subscripts, etc.

## Section "Theoretical background".

### Subsection "Explicit network model"

- **Page 12, Line 312 and Page 13, Lines 316 and 317-318.** Use another notation to write  $SF_j$  (this is a bit confusing). Something like j-th simple fracture or j-th SF.
- **Page 12, Line 312.** You write “schematized by a 1d – pipe element”. Use better 1 D-pipe element.
- **Page 13, Lines 319 and 322.** Write 2D instead of 2d.
- **Page 14, Line 339.** Write the convolution operator without parenthesis: \*.
- **Page 14, Line 340.** The notation for the inverse Laplace transform operator,  $L^{-1}$ , could be mistaken for the characteristic length, L. Use another notation.
- **Page 14, Lines 348-349.** Modify the phrase as follows: Where  $T_0$  (K) is the initial temperature,  $T_{inj}$  (K) is the temperature injection function and  $P_{H,j}$  is the heat distribution probability.

## Section "Material and methods"

### Subsection "Description of the experimental apparatus"

- **Page 15, Lines 375.** Verify the writing of the units:  $\mu\text{S cm}^{-1}$ .

## Section "Results and discussion"

### Subsection "Flow characteristics"

- **Page 16, Line 406.** Write 2D instead of 2d.
- **Page 17, Line 417.** Write  $Fo=1$  in italics.

## Section "Results and discussion"

### Subsection "Fitting of breakthrough curves and interpretation of estimated model parameters"

- **Page 17. Line 430.** It is better to indicate the number of the section you refer, and not “the previous section”.
- **Page 17. Line 433.** Review the number of the equations quoted: Are not equations 36 and 37?
- **Page 17. Lines 441 to 444.** You would quote Tables 1 and 2 in this paragraph to verify the conclusions deduced in these lines.
- **Page 18. Lines 448 to 451.** The same as before: you would quote Tables 1 and 2 in this paragraph to verify the conclusions deduced in these lines.
- **Page 18. Line 468.** You write: “whereas  $u_f$  is influenced”. Add a blank space.

## References

Review all the bibliographic references.

Review the NPG format for references because there are several references that are not well written (the punctuation, the initial page or the final page, the position of the year is not at the end or the review is not written in italics). For example, the following references are not correct:

- Auradou, H., Deazerm G., Boschan, A., Hulin J., Koplik, J., 2006. Flow channeling in a single fracture induced by shear displacement. *Geothermics* 35 575-588.
- Becker, M.W. and Shapiro, A. M., 2003. Interpreting tracer breakthrough tailing from different forced gradient tracer experiment configurations in fractured bedrock. *Water Resources Research*. 39(1):1024. pages.
- Cherubini, C., Pastore, N., 2011. Critical stress scenarios for a coastal aquifer in southeastern Italy. *Natural Hazards and Earth System Science*. 11 (5) p. 1381-1393.

And more.

I do not understand the following reference:

- Geiger, S. and Emmanuel, S., 2010. Non-fourier thermal transport in fractured geological media. *Water Resources Research*, 46, xvii, 26, 27, 168.

The following references are not quoted in the text but they are in the list:

- De Hoog, F.R., Knight, J.H., Stokes, A.N., 1982. An improved method for numerical inversion of Laplace transforms. *SIAM J. Sci. Stat. Comput.* 3 (3), 357-366.
- Hasler, A., Gruber, S., Font, M., Dubois, A., 2011. Advective heat transport in frozen rock cleft – Conceptual model, laboratory experiments and numerical simulation.....pages?

You quote in the text some references but there are no corresponding bibliographic references in the list:

- Neuville et al. (2010)
- All quotes in page 4 are not in the reference list.
- Hopmans et al. (2002).
- Sauty et al. (1982)
- Papadopoulos and Larson, 1978.
- Smith and Chapman, 1983.
- Molson et al., 1992.

- De Marsily, 1986.
- Anderson, 2005.
- Hatch et al., 2006.
- Keery et al., 2007.
- Vandenbohede et al., 2009.
- Vandenbohede and Lebbe, 2010.
- Rau et al., 2010.
- Green et al., 1964.
- Wu et al., 2010.

You mention the following reference (Cherubini et al., 2013) in the text (page 9, line 233 and page 18, line 457) but you write four different references in the list: 2013a, 2013b, 2013c and 2013d. Which is the reference you want to quote? All?

Use the same line spacing in the reference list (see page 25 from line 657 to 668 and page 26 from line 669 to 674).

The following reference (page 26, line 673 to 674):

Martinez, A. R., Roubinet, D., Tartakovsky, D. M., 2014. Analytical models of heat conduction in fractured rocks. *J. Geophys. Res. Solid Earth*, 119.

is not in a separate line from the previous bibliographic reference.

### Tables

- **Table 1 and 2**

Modify the caption to include the definition of  $Q_o$ ,  $u_f$ ,  $D_f$  and  $\alpha$ .

### Figures

- **Figure 1.** It would be interesting to add a photograph of the experimental setup in Figure 1.
- **Figure 2.** Modify the caption to include the definition of  $Q_o$ ,  $Q_1$  and  $Q_2$ . Is it possible to use a frontal figure and not this tilted one? May be, it is also possible to say that is an extension of the rock matrix in Figure 1.
- **Figure 3.** The label of the Y-axis in the upper left figure is different from the others Y-labels.
- **Figure 4.** Describe the meaning of the blue curve in the caption.
- *Figure 7 is not quoted in the text.*
- **Figure 12.** Review the writing of the symbols  $D_a$  and  $Q_o$  with and without subscripts in the text, in the caption of this figure and in the labels of the axis.
- **Figure 15.** Use smaller symbols as in the previous figures.