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LABORATORY EXPERIMENTAL INVESTIGATION OF HEAT TRANSPORT IN FRACTURED MEDIA

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Abstract

Low enthalpy geothermal energy is a renewable resource that is still underexploited nowadays, in relation to its potential for development in the society worldwide. Most of its applicabilities have already been investigated, such as: heating and cooling of private and public buildings, roads defrost, cooling of industrial processes, food drying systems, desalination.

One of the major limitations related to the choice of installing low enthalpy geothermal power plants regards the initial investment costs.

In order to increase the optimal efficiency of installations which use groundwater as geothermal resource, flow and heat transport dynamics in aquifers need to be well characterized. Especially in fractured rock aquifers these processes represent critical elements that are not well known. Therefore there is a tendency to oversize geothermal plants.

In literature there are very few studies on heat transport especially in fractured media.

This study is aimed to deepen the understanding of this topic through heat transport experiments in fractured network and their interpretation.

The heat transfer tests have been carried out on the experimental apparatus previously employed to perform flow and tracer transport experiments, which has been modified in order to analyze heat transport dynamics in a network of fractures. In order to model the obtained thermal breakthrough curves, the Explicit Network Model (ENM) has been used, which is based on an adaptation of a Tang's solution for the transport of the solutes in a semi-infinite single fracture embedded in a porous matrix.

Parameter estimation, time moment analysis, tailing character and other dimensionless parameters have permitted to better understand the dynamics of heat transport and the efficiency of heat exchange

between the fractures and matrix. The results have been compared with the previous experimental studies on solute transport.

Introduction

An important role in transport of natural resources or contaminant transport through subsurface systems is given by fractured rocks. The interest about the study of dynamics of heat transport in fractured media has grown in recent years because of the development of a wide range of applications, including geothermal energy harvesting (Gisladottir et al., 2016).

Quantitative geothermal reservoir characterization using tracers is based on different approaches for predicting thermal breakthrough curves in fractured reservoirs (Shook, 2001, Kocabas, 2005, Read et al. 2013).

The characterization and modeling of heat transfer in fractured media is particularly challenging as open and well-connected fractures can induce highly localized pathways which are orders of magnitude more permeable than the rock matrix (Klepikova et al, 2016, Cherubini and Pastore, 2011). The study of solute transport in fractured media has become recently a widely diffused research topic in hydrogeology (Cherubini, 2008, Cherubini et al., 2008, Cherubini et al., 2009, Masciopinto et al., 2010), whereas the literature about heat transfer in fractured media is somewhat limited.

Hao et al. (2013) developed a dual continuum model for the representation of discrete fractures and the interaction with surrounding rock matrix in order to give a reliable prediction of the impacts of fracture – matrix interaction on heat transfer in fractured geothermal formations.

Moonen et al. (2011) introduced the concept of cohesive zone which represents a transition zone between the fracture and undamaged material. They proposed a model to adequately represent the influences of fractures or partially damaged material interfaces on heat transfer phenomena.

Geiger and Emmanuel (2010) found that matrix permeability plays an important role on thermal retardations and attenuation of thermal signal. At high matrix permeability, poorly connected fractures can contribute to the heat transport, resulting in heterogeneous heat distributions in the whole matrix block. For lower matrix permeability heat transport occurs mainly through fractures that form a fully connected pathway between the inflow and outflow boundaries, that results in highly non – Fourier behavior, characterized by early breakthrough and long tailing.

Numerous field observations (Tsang and Neretnieks, 1998) show that flow in fractures is being organized in channels due to the small scale variations in the fracture aperture. Flow channeling causes dispersion in fractures. Such channels will have a strong influence on the transport characteristics of a fracture, such as, for instance, its thermal exchange area, crucial for geothermal

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applications (Auradou et al., 2006). Highly channelized flow in fractured geologic systems has been credited with early thermal breakthrough and poor performance of geothermal circulation systems (Hawkins et al., 2012).

Lu et. Al (2012) conducted experiments of saturated water flow and heat transfer in a regularly fractured granite at meter scale. The experiments indicated that the heat advection due to water flow in vertical fractures nearest to the heat sources played a major role in influencing the spatial distributions and temporal variations of the temperature, impeding the heat conduction in transverse direction; such effect increased with larger water fluxes in the fractures and decreased with higher heat source and/or larger distance of the fracture from the heat source.

Neuville et al. (2010) showed that fracture – matrix thermal exchange is highly affected by the fracture wall roughness. Natarajan et. al (2010) conducted numerical simulation of thermal transport in a sinusoidal fracture matrix coupled system. They affirmed that this model presents a different behavior respect to the classical parallel plate fracture matrix coupled system. The sinusoidal curvature of the fracture provides high thermal diffusion into the rock matrix.

Ouyang (2014) developed a three – equation local thermal non – equilibrium model to predict the effective solid – to – fluid heat transfer coefficient in the geothermal system reservoirs. They affirmed that due to the high rock – to – fracture size ratio, the solid thermal resistance effect in the internal rocks cannot be neglected in the effective solid – to fluid heat transfer coefficient. Furthermore the results of this study show that it is not efficient to extract the thermal energy from the rocks if fracture density is not large enough.

Analytical and semi-analytical approaches have been developed to describe the dynamics of heat transfer in fractured rocks. Such approaches are amenable to the same mathematical treatment as their counterparts developed for mass transport (Martinez et al., 2014). One of these is the analytical solution derived by Tang et al. (1981).

While the equations of solute and thermal transport have the same basic form, the fundamental difference between mass and heat transport is that: 1) solutes are transported through the fractures only, whereas heat is transported through both fractures and matrix, 2) the fracture-matrix exchange is large compared with molecular diffusion. This means that the fracture matrix exchange is more relevant for heat transport than for mass transport. Thus, matrix thermal diffusivity strongly influences the thermal breakthrough curves (BTCs) (Becker and Shapiro, 2003).

Contrarily, since the heat capacity of the solids will retard the advance of the thermal front, the advective transport for heat is slower than for solute transport (Rau et al., 2012).

The quantification of thermal dispersivity as far as heat transport and its relationship with velocity hasn't been properly addressed experimentally and has got conflicting descriptions in literature (Ma et al, 2012).

Most studies neglect the hydrodynamic component of thermal dispersion because of thermal diffusion being more efficient than molecular diffusion by several orders of magnitude (Bear 1972). Analysis of heat transport under natural gradients has commonly neglected hydrodynamic dispersion (e.g., Bredehoeft and Papadopulos 1965; Domenico and Palciauskas 1973; Taniguchi et al. 1999; Reiter 2001; Ferguson et al. 2006). Dispersive heat transport is often assumed to be represented by thermal conductivity and/or to have little influence in models of relatively large systems and modest fluid flow rates (Bear, 1972, Woodbury and Smith, 1985).

Some authors suggest that thermal dispersivity enhances the spreading of thermal energy and should therefore be part of the mathematical description of heat transfer in analogy to solute dispersivity (de Marsily, 1986) and have incorporated this term into their models (e.g., Smith and Chapman, 1983; Hopmans et al., 2002; Niswonger and Prudic, 2003). In the same way, other researchers (e.g. , Smith and Chapman, 1983, Ronan et al., 1998, Constanz et al., 2002, Su et al., 2004) have included the thermomechanical dispersion tensor representing mechanical mixing caused by unspecified heterogeneities within the porous medium.

On the contrary, some other researchers argue that the enhanced thermal spreading is either negligible or can be described simply by increasing the effective diffusivity, thus the hydrodynamic dispersivity mechanism is inappropriate. (Bear, 1972; Bravo et al., 2002, Ingebritsen and Sanford, 1998, Keery et al, 2007). Constantz et al. (2003) and Vandenbohede et al. (2009) found that thermal dispersivity was significantly smaller than the solute dispersivity. Others (de Marsily, 1986, Molina-Giraldo et al., 2011) found that thermal and solute dispersivity were on the same order of magnitude.

Tracer tests of both solute and heat were carried out at Bonnaud, Jura, France (deMarsily 1986) and the thermal dispersivity and solute dispersivity were found of the same order of magnitude.

Bear (1972), Ingebritsen and Sanford (1998), and Hopmans et al. (2002), among others, concluded that the effects of thermal dispersion are negligible compared to conduction and set the former to zero.

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However, Hopmans et al (2002) showed that dispersivity is increasingly important at higher flow water velocities, since it is only then that the thermal dispersion term is of the same order of magnitude or larger than the conductive term.

Sauty et al. (1982) suggested that there was a correlation between the apparent thermal conductivity and Darcy velocity thus they included the hydrodynamic dispersion term in the advective-conductive modeling.

Other similar formulations of this concept are present in the literature (e.g., Papadopulos and Larson 1978; Smith and Chapman 1983; Molson et al. 1992). Such treatments have not explicitly distinguished between macrodispersion, which occurs due to variations in permeability over larger scales and the components of hydrodynamic dispersion that occur due to variations in velocity at the pore scale.

One group of authors have utilized a linear relationship to describe the thermal dispersivity and the relationship between thermal dispersivity and fluid velocity (e.g., 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), while others have identified the possibility of a nonlinear relationship (Green et al., 1964).

In previous studies by Cherubini et al. (2012, 2013a, 2013b, 2013c and 2014) the presence of nonlinear flow and non – Fickian transport in a fractured rock formation has been detected. The experimental results showed evidence of a non-Darcy relationship between hydraulic head differences and flow rate that is best described by a Forchheimer law.

Between the Forchheimer terms and the tortuosity factor a power law has been detected, which means that the latter influences flow dynamics. Tracer tests were performed to analyse the non - Fickian nature of transport.

The 2 – D Explicit Network Model (ENM) has provided the best fit of the observed experimental solute BTCs. This approach depicts the fractures as 1-D pipe elements forming a 2-D pipe network and therefore expressly takes the fracture network geometry into account. The ENM model permits to understand the physical meaning of flow and transport phenomena and therefore to obtain a more accurate estimation of flow and transport parameters.

In this study, in order to investigate the behavior of heat transport in a fractured network, thermal tracer tests have been carried out on the same artificially created fractured rock sample.

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A better development of the Explicit Network Model (ENM) based on a Tang's solution developed for solute transport in a single semi-infinite fracture inside a porous matrix has been used for the fitting of the thermal BTCs.

In analogous way the ENM model has been used in order to fit the observed BTCs obtained from previous experiments on mass transport. The obtained thermal BTCs show a more enhanced early arrival and long tailing than solute BTCs.

The travel time for solute transport is an order of magnitude lower than for heat transport experiments. Thermal convective velocity is thus more delayed respect to solute transport. The thermal dispersion mechanism dominates heat propagation in the fractured medium in the carried out experiments and thus cannot be neglected.

For mass transport the presence of the secondary path and the nonlinear flow regime are the main factors affecting non – Fickian behavior observed in experimental BTCs, whereas for heat transport non - Fickian nature of the experimental BTCs is governed mainly by the heat exchange mechanism between the fracture network and the surrounding matrix. The presence of a nonlinear flow regime gives rise to a weak growth on heat transfer phenomena.

Furthermore the estimation of the average effective thermal conductivity suggests that there is a solid thermal resistance in the fluid to solid heat transfer processes due to the rock – fracture size ratio. This result matches previous analyses (Pastore et al., 2015) in which a lower heat dissipation respect to the Tang's solution in correspondence of the single fracture surrounded by a matrix with more limited heat capacity has been found.

Theoretical background

Nonlinear flow

With few exceptions, any fracture can be envisioned as two rough surfaces in contact. In cross section the solid areas representing asperities might be considered as the grains of porous media.

Therefore, in most studies examining hydrodynamic processes in fractured media, the general equations describing flow and transport in porous media are applied, such as Darcy's law, that depicts a linear relationship between the pressure gradient and fluid velocity (Whitaker, 1986; Cherubini and Pastore, 2010a)

However, this linearity has been demonstrated to be valid at low flow regimes ($Re < 1$). For $Re > 1$ a nonlinear flow behavior is likely to occur (Cherubini, 2013d).

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When Re >> 1, a strong inertial regime develops, that can be described by the Forchheimer equation (Forchheimer, 1901):

$$-\frac{dp}{dx} = \frac{\mu}{k} \cdot u_f + \rho\beta \cdot u_f^2 \tag{1}$$

Where β (L^{-1}) is called the inertial resistance coefficient, or non – Darcy coefficient.

It is possible to express Forchheimer law in terms of hydraulic head:

$$-\frac{dh}{dx} = a' \cdot u_f + b' \cdot u_f^2 \tag{2}$$

The coefficients *a* (TL^{-1}) and *b* (TL^{-2}) represent the linear and inertial coefficient respectively equal to:

$$a' = \frac{\mu}{\rho g k};\ b' = \frac{\beta}{g} \tag{3}$$

The relationship between hydraulic head gradient and flow rate *Q* (L^3T^{-1}) can be written as:

$$-\frac{dh}{dx} = a \cdot Q + b \cdot Q^2 \tag{4}$$

The coefficients *a* (TL^{-3}) and *b* (T^2L^{-6}) can be related to *a'* and *b'*:

$$a = \frac{a'}{\omega_{eq}}; b = \frac{b'}{\omega_{eq}} \tag{5}$$

Where ω_{eq} (L^2) is the equivalent cross sectional area of fracture.

Heat transfer by water flow in single fractures

Fluid flow and heat transfer in a single fracture (*SF*) undergo advective, diffusive and dispersive phenomena. Dispersion is caused by small scale fracture aperture variations. Flow channeling is one example of macrodispersion caused by preferred flow paths, in that mass and heat tend to migrate through the portions of a fracture with the largest apertures.

In fractured media another process is represented by diffusion into surrounding rock matrix. Matrix diffusion attenuates the mass and heat propagation in the fractures.

According to the boundary – layer theory (Fahien, 1983), solute mass transfer q_m (ML^{-2}) per unit area at the fracture-matrix interface (Wu et al., 2010) is given by:

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$$q_M = \frac{D_m}{\delta}\left(c_f - c_m\right) \quad (6)$$

Where c_f (ML^{-3}) is the concentration across fractures, c_m (ML^{-3}) is the concentration of the matrix block surfaces, D_m (LT^{-2}) is the molecular diffusion coefficient, and δ (m) is the thickness of boundary layer (Wu et al., 2010). For small fractures, δ may become the aperture w_f (m) of the *SF*.

In analogous manner the specific heat transfer flux q_H (MT^{-3}) at the fracture – matrix interface is given by:

$$q_H = \frac{k_m}{\delta}\left(T_f - T_m\right) \quad (7)$$

Where T_f (K) is the temperature across fractures, T_m (K) is the temperature of the matrix block surfaces, k_m ($MLT^{-3}K^{-1}$) is the thermal conductivity.

The continuity conditions at the fracture – matrix interface requires a balance between mass transfer rate and mass diffused into the matrix described as:

$$q_M = -D_e \left.\frac{\partial C_m}{\partial z}\right|_{z=w_f/2} \quad (8)$$

Where z (m) is the coordinate perpendicular to the fracture axis and w_f is the aperture of the fracture.

In the same way the specific heat flux must be balanced by heat diffused into the matrix described as:

$$q_H = -k_e \left.\frac{\partial T_m}{\partial z}\right|_{z=w_f/2} \quad (9)$$

The effective terms (D_e instead of D_m and k_e instead of k_m) have been introduced in order to include the effect of various system parameters such as fluid velocity, porosity, surface area, roughness, that may enhance mass and heat transfer effect. For instance, when large flow velocity occurs, convective transport is stronger along the centre of the fracture, enhancing the concentration or temperature gradient at the fracture matrix interface. As known roughness plays an important role in increasing mass or heat transfer because of increasing turbulent flow conditions.

According to Bodin (2007) the governing equation for the one dimensional advective - dispersive transport along the axis of a semi-infinite fracture with one – dimensional diffusion in the rock matrix, in perpendicular direction to the axis of the fracture is:

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$$\frac{\partial c_f}{\partial t}+u_f\frac{\partial c_f}{\partial x}=\frac{\partial}{\partial x}\left(D_f\frac{\partial c_f}{\partial x}\right)-\frac{D_e}{\delta}\frac{\partial c_m}{\partial z}\bigg|_{z=w_f/2} \tag{10}$$

Where x (m) is the coordinate parallel to the axis of *SF*, u_f (LT^{-1}) is the convective velocity, D_f (L^2T^{-1}) is the dispersion coefficient. The latter mainly depends on two processes: Aris – Taylor dispersion and geometrical dispersion. Previous experiments (Cherubini et al., 2013) show that, due to the complex geometrical and topological characteristics of the fracture network that create tortuous flow paths, Aris – Taylor dispersion may not develop. A linear relationship has been found between velocity and dispersion so geometrical dispersion is mostly responsible for the mixing process along the fracture:

$$D_f=\alpha_{LM}u_f \tag{11}$$

Where α_{LM} (L) is the dispersion coefficient for mass transport.

Assuming that fluid flow velocity in the surrounding rock matrix is equal to zero, the equation for the conservation of heat in the matrix is given by:

$$\frac{\partial C_m}{\partial t}=D_a\frac{\partial^2 C_m}{\partial z^2} \tag{12}$$

Where D_a is the apparent diffusion coefficient of the solute in the matrix expressed as function of θ_m (-) the matrix porosity $D_a=D_e/\theta_m$ (Bodin et al., 2007). Tang et al. (1981) presented an analytical solution for solute transport in semi – infinite single fracture embedded in a porous rock matrix with a constant concentration at the fracture inlet ($x = 0$) equal to c_0 (ML^{-3}) and with an initial concentration equal to zero. The solute concentration in the fracture $\overline{c}_f$ and in the matrix $\overline{c}_m$ has been given as function of time in Laplace space.

$$\overline{c}_f=\frac{c_0}{s}\exp(vL)\exp\left[-vL\left\{1+\beta^2\left(\frac{s^{1/2}}{A}+s\right)\right\}^{1/2}\right] \tag{13}$$

$$\overline{c}_m=\overline{c}_f\exp\left[-Bs^{1/2}\left(z-w_f/2\right)\right] \tag{14}$$

Whereas the gradient of $\overline{c}_m$ at the interface $z = w_f/2$ is:

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$$\left.\frac{d\bar{c}_m}{dx}\right|_{x=w_f/2} = -\bar{c}_f B s^{1/2} \tag{15}$$

The v, A, β^2 and B coefficients are expressed as follows:

$$v = \frac{u_f}{2D_f} \tag{16}$$

$$A = \frac{\delta}{\sqrt{\theta D_e}};\ \theta = \theta_m \tag{17}$$

$$\beta^2 = \frac{4D_f}{u_f^2} \tag{18}$$

$$B = \frac{1}{\sqrt{D_e}} \tag{19}$$

Furthermore on the basis of these analytical solutions the probability density function of the solute residence time (*PDF*) in the single fracture in the Laplace space can be expressed as:

$$\bar{\Gamma}(s) = \exp(vL)\exp\left[-vL\left\{1+\beta^2\left(\frac{s^{1/2}}{A}+s\right)\right\}^{1/2}\right] \tag{20}$$

Assuming that density and heat capacity are constant in time, the heat transport conservation equation in *SF* can be expressed as follows:

$$\frac{\partial T_f}{\partial t} + u_f\frac{\partial T_f}{\partial x} = \frac{\partial}{\partial x}\left(D_{fH}\frac{\partial T_f}{\partial x}\right) - \frac{k_e}{\rho_w C_w \delta}\left.\frac{\partial T_m}{\partial z}\right|_{z=w_f/2} \tag{21}$$

Where ρ_w (ML^{-3}), C_w ($L^2T^2K^{-1}$) represent the density, the specific heat capacity of the fluid within *SF* respectively. D_f for heat transport assumes the following expressions:

$$D_{fH} = \frac{\lambda_L}{\rho_w C_w} \tag{22}$$

Where λ_L is the thermodynamic dispersion coefficient ($MLT^{-3}K^{-1}$). Sauty et al. (1982) and de Marsily (1986) proposed an expression for the thermal dispersion coefficient where the thermal dispersion term varies linearly with velocity and depends on the heterogeneity of the medium, as for solute transport:

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$$\lambda_L = k_0 + \alpha_{LH} \rho_w c_w u_f \tag{23}$$

Where k_0 is the bulk thermal conductivity ($MLT^{-3}K^{-1}$) α_{LH} (L) is the longitudinal thermal dispersivity.

The heat transport conservation equation in the matrix is expressed as follows:

$$\rho_m C_m \frac{\partial T_m}{\partial t} = k_e \frac{\partial^2 T_m}{\partial z^2} \tag{24}$$

Note that the governing equations of heat and mass transport highlight similarities between the two processes, thus Tang's solution can be used also for heat transport.

In terms of heat transport, the coefficients v, A, β^2 and B are expressed as follows:

$$v = \frac{u_f}{2D_{fH}}; \tag{25}$$

$$A = \frac{\delta}{\sqrt{\theta D_e}}; \quad \theta = \frac{\rho_m C_m}{\rho_f C_f}, \quad D_e = \frac{k_e}{\rho_w C_w} \tag{26}$$

$$\beta^2 = \frac{4D_f}{u_f^2} \tag{27}$$

$$B = \frac{1}{\sqrt{D_e}} \tag{28}$$

Three characteristic time scales can be defined:

$$t_u = \frac{L}{u_f}; \quad t_d = \frac{L^2}{D_f}; \quad t_e = \frac{\delta^2}{D_e} \tag{29}$$

Where L (L) is the characteristic length, t_u (T), t_d (T) and t_e (T) represent the characteristics time scales of convective transport, dispersive transport and loss of the mass or heat into the surrounding matrix.

The relative effect of dispersion, convection and matrix diffusion on mass or heat propagation in the fracture can be evaluated by comparing the correspondent time scale.

Peclet number P_e is defined as the ratio between convective to dispersive transport times:

$$Pe = \frac{t_d}{t_u} = \frac{u_f L}{D_f} \tag{30}$$

At high Peclet numbers transport processes are mainly governed by convection, whereas at low Peclet numbers it is mainly dispersion that dominates.

Another useful dimensionless number, generally applied in chemical engineering, is the Damköhler number that can be used in order to evaluate the influence of matrix diffusion on convection phenomena. The Damköhler number is based on the exchange rate coefficient corresponding to:

$$\alpha = \frac{D_e}{\delta^2} \tag{31}$$

Note that the inverse of t_e has the same meaning of the exchange rate coefficient α (T^{-1}). D_a relates the convection time scale to the exchange time scale.

$$Da = \frac{t_u}{t_e} = \frac{\alpha L}{u_f} \tag{32}$$

When t_e values are of the same order of magnitude as the transport time t_u ($D_a \cong 1$), diffusive processes in the matrix are more relevant. In this case concentration or temperature distribution profiles are characterized by a long tail.

When $t_e \gg t_u$ ($D_a \ll 1$) the fracture – matrix exchange is very slow and it does not influence mass or heat propagation. On the contrary when $t_e \ll t_u$ ($D_a \gg 1$) the fracture matrix exchange is rapid, there is instantaneous equilibrium between fracture and matrix and they have the same concentration or temperature. These two circumstances close the standard advective – dispersive transport equation.

The product between Pe and Da represents another dimensionless group which is a measure of transport processes:

$$Pe \times Da = \frac{t_d}{t_e} = \frac{\alpha L^2}{D_f} \tag{33}$$

When $Pe \times Da$ increases t_e decreases more rapidly than t_d, and subsequently the mass or heat diffusion into the matrix may be dominant on the longitudinal dispersion.

Explicit network model (ENM)

With the assumption that a *SF j* can be schematized by a 1d – pipe element, the Forchheimer model can be used to write the relationship between head loss Δh_j (L) and flow rate Q_j (L^3T^{-1}) in finite terms:

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$$\frac{\Delta h_j}{L_j} = aQ_j + bQ_j^2 \Rightarrow \Delta h_j = \left[L_j \left(a + bQ_j \right) \right] Q_j \tag{34}$$

Where L_j (L) is the length of *SF j*, *a* (TL^{-3}) and *b* (T^2L^{-6}) represent the Forchheimer parameters written in finite terms. The term in the square brackets constitutes the resistance to flow $R_j\left(Q_j\right)$ (TL^{-2}) of *SF j*.

In case of steady – state conditions and for a simple 2d fracture network geometry, a straightforward manner can be applied to obtain the solution of flow field by applying the first and second Kirchhoff's laws.

In a 2d fracture network, fractures can be arranged in series and/or in parallel. Specifically, in a network in which fractures are set in a chain, the total resistance to flow is calculated by simply adding up the resistance values of each single fracture. The flow in a parallel fracture network breaks up, with some flowing along each parallel branch and re – combining when the branches meet again. In order to estimate the total resistance to flow the reciprocals of the resistance values have to be added up and then the reciprocal of the total has to be calculated. The flow rate Q_j across the generic fracture *j* of the parallel network can be calculated as (Cherubini et al., 2014):

$$Q_j = \sum Q \left[\frac{1}{R_j} \left(\sum_{i=1}^{n} \frac{1}{R_i} \right)^{-1} \right] \tag{35}$$

Where $\sum Q$ (LT^{-3}) is the sum of the mass flow rates at fracture intersections in correspondence of the inlet bond of *j* fracture, whereas the term in square brackets represents the probability of water distribution of *j* fracture $P_{Q,j}$.

Once known the flow field in the fracture network, to obtain the *PDF* at a generic node the *PDFs* of each elementary path that reaches the node have to be summed up. They can be calculated as the convolution product of the *PDFs* of each single fracture composing the elementary path.

Definitely the BTC describing the concentration in the fracture as function of time at the generic node, using the convolution theorem, can be obtained as follows:

$$c_f\left(t\right) = c_0 + c_{inj}\left(t\right) * L^{-1}\left[\sum_{i=1}^{N_p} \prod_{j=1}^{n_{f,i}} P_{M,j} \overline{\Gamma}_j\left(s\right) \right] \tag{36}$$

Where c_0 (ML^{-3}) is the initial concentration and c_{inj} (ML^{-3}) is the concentration injection function, ($*$) is the convolution operator, L^{-1} represents the inverse Laplace transform operator, N_p is the number of the paths that reach the node, $n_{f,i}$ is the number of the *SF* belonging to the elementary path i^{th}, $P_{M,j}$ and $\overline{\Gamma}(s)$ are the mass distribution probability and the *PDF* in the Laplace space of the generic j^{th} *SF* respectively. Inverse Laplace transform L^{-1} can be solved numerically using Abate et al. (2006) algorithm.

At the same way the BTC T_f which describes the temperature in the fracture as function of time at the generic node can be written as:

$$T_f(t) = T_0 + T_{inj}(t) * L^{-1}\left[\sum_{i=1}^{N_p}\prod_{j=1}^{n_{f,i}} P_{H,j}\overline{\Gamma}_j(s)\right] \tag{37}$$

Where T_0 (K) is the initial temperature and T_{inj} (K) is the temperature injection function, $P_{H,j}$ is the heat distribution probability.

$P_{\mathrm{M},j}$ and $P_{\mathrm{H},j}$ can be estimated as the probabilities of the mass and heat distribution at the inlet bond of each individual *SF* respectively. The mass and heat distribution is proportional to the correspondent flow rates:

$$P_{\mathrm{M},j} = P_{H,j} = \frac{Q_j}{\sum Q} \tag{38}$$

Where Q_j is the flow rate in the *j SF* and $\sum Q$ is the sum of the flow rate calculated at the fracture intersection in correspondence of the inlet bond of *j* fracture. Note that if Equation 37 is valid, the probability of water distribution is equal to the probabilities of mass and heat distribution (term in square brackets in Equation 34). Definitely the ENM model regarding each *SF* can be described by four parameters ($u_{f,j}$, $D_{f,j}$, α_j, $P_{Q,j}$).

Material and methods

Description of the experimental apparatus

The heat transfer tests have been carried out on the experimental apparatus previously employed to perform flow and tracer transport experiments at bench scale (Cherubini et al. 2012, 2013a, 2013b, 2013c and 2014). However, the apparatus has been modified in order to analyze heat transport dynamics. Two thermocouples have been placed at the inlet and the outlet of a selected fracture path

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of the limestone block with parallelepiped shape (0.6×0.4×0.08 m^3) described in previous studies. A TC – 08 Thermocouple Data Logger (pico Technology) with a sampling rate of 1 second has been connected to the thermocouples. An extruded polystyrene panel with thermal conductivity equal to 0.034 $Wm^{-1}K^{-1}$ and thickness 0.05 m has been used to thermally insulate the limestone block which has then been connected to a hydraulic circuit. The difference in hydraulic head between the upstream tank connected to the inlet port and the downstream tank connected to the outlet port drives flow of water through the fractured block. An ultrasonic velocimeter (DOP3000 by Signal Processing) has been adopted to measure the instantaneous flow rate that flows across the block. An electric boiler with a volume of 10^{-2} m^3 has been used to heat the water. In a flow cell located in correspondence of the outlet port a multiparametric probe is positioned for the instantaneous measurement of pressure (dbar), temperature (°C) and electric conductivity (μS cm−1). The schematic diagram of the experimental apparatus is shown in Figure 1.

Flow experiments.

The average flow rate through the selected path can be evaluated as:

$$\bar{Q} = \frac{S_1}{t_1 - t_0}(h_1 - h_0) \tag{39}$$

Where S_1 (L^2) is the cross section area of the flow cell, $\Delta t = t_1 - t_0$ is the time for the flow cell to be filled from h_0 (L) and h_1 (L). To calculate the average hydraulic head differences between the upstream tank and the flow cell the following expression is adopted:

$$\Delta h = h_c - \frac{h_0 + h_1}{2} \tag{40}$$

Where h_c is the hydraulic head measured in the upstream tank. Several tests have been carried out varying the control head, and in correspondence of each value of the average flow rate and head differences the average resistance to flow has been determined as:

$$\bar{R}(\bar{Q}) = \left[\frac{S_1}{t_1 - t_0}\ln\left(\frac{h_0 - h_c}{h_1 - h_c}\right)\right]^{-1} \tag{41}$$

Solute and temperature tracer tests

Solute and temperature tracer tests have been conducted through the following steps.

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As initial condition, a specific value of hydraulic head difference between the upstream tank and downstream tank has been assigned. At t = 0 the valve a is closed so as the hydrostatic head inside the block assumes the same value to the one in the downstream tank. At t = 10 s the valve a is opened.

For solute tracer test at time t = 60 s by means of a syringe, a mass of 5×10^{-4} kg sodium chloride is injected into the inlet port. Due to the very short source release time, the instantaneous source assumption can be adopted. The multiparametric probe located within the flow cell measures the solute BTC.

As concerns thermal tracer tests at the time t = 60 s the valve d is opened while the valve c is closed. In such a way a step temperature function in correspondence of the inlet port $T_{inj}(t)$ is imposed and measured by the first thermocouple. The other thermocouple located inside the outlet port is used to measure the thermal BTC.

The ultrasonic velocimeter is used in order to measure the instantaneous flow rate, whereas a multiparametric probe located at the outlet port measures the pressure and the electric conductivity.

Results and discussion

Flow characteristics

The Kirchhoff laws have been used in order to estimate the flow rates flowing in each single fracture. In figure 2 a sketch of the 2d pipe conceptualization of the fracture network is reported.

The linear and nonlinear terms have been assumed equal for each single fracture of the fracture network and have been estimated matching the average experimental resistance to flow resulting from Equation (41) with resistance to flow estimated as:

$$\bar{R}(\bar{Q}) = R_1(Q_0)+R_2(Q_0)+\left(\frac{1}{R_6(Q_1)}+\frac{1}{R_3(Q_2)+R_4(Q_2)+R_5(Q_2)}\right)^{-1}+ \\ +R_7(Q_0)+R_8(Q_0)+R_9(Q_0) \tag{42}$$

The flow rate Q_1 is determined using the following iterative equation:

$$Q_1^{k+1} = Q_0\left[\frac{R_3(Q_0-Q_1^k)+R_4(Q_0-Q_1^k)+R_5(Q_0-Q_1^k)}{R_3(Q_0-Q_1^k)+R_4(Q_0-Q_1^k)+R_5(Q_0-Q_1^k)+R_6(Q_1^k)}\right] \tag{43}$$

Whereas the flow rate Q_2 is determined merely as:

$$Q_2 = Q_0 - Q_1 \tag{44}$$

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The linear and nonlinear term are equal respectively to $a = 7.345\times10^4$ sm^{-3} and b=11.65×10^9 s^{2}m^{-6}. Inertial forces dominate viscous ones when the Forchheimer number is higher than one. The critical flow rate Q_{crit} can be determined in correspondence of Fo = 1 as the ratio between a and b resulting $Q_{crit} = 6.30\times10^{-6}$ m^{3}s^{-1}.

Because of the nonlinearity of flow, varying the inlet flow rate Q_0 the ratio between the flow rates Q_1 and Q_2 flowing respectively in the branches 6 and 3 – 5 is not constant. When Q_0 increases Q_2 increases faster than Q_1. The probability of water distribution of the branch 6 $P_{Q,6}$ is evaluated as the ratio between Q_0 and Q_1, whereas the probability of water distribution of the branch 3 – 5 is equal to $P_{Q,3\text{-}5} = 1 - P_{Q,6}$.

Fitting of breakthrough curves and interpretation of estimated model parameters

The behavior of mass and heat transport has been compared varying the injection flow rates. In particular 21 tests in the range 1.83×10^{-6} - 1.26×10^{-5} m^{3}s^{-1} for heat transport have been made and compared with the 55 tests in the range 1.32×10^{-6} - 8.34×10^{-6} m^{3}s^{-1} for solute transport presented in previous studies.

The observed heat and mass BTCs for different flow rates have been individually fitted using the ENM approach presented in the previous section. The transport parameters u_f, D_f and α are assumed equal for all branches of the fracture network. The probability of mass and heat distribution are assumed equal to the probability of water distribution.

The experimental BTCs are fitted using Equation 35 and Equation 36 for mass and heat transport respectively. Note that for mass transport $c_{inj}(t)$ supposing the instantaneous injection condition becomes a Dirac delta function.

The determination coefficient (r^2) and the root mean square error ($RMSE$) have been used in order to evaluate the goodness of fit.

Tables 1 and 2 show the values of transport parameters, the $RMSE$ and r^2 for mass and heat transport respectively. Furthermore Figure 3 and Figure 4 show the fitting results of BTCs for some values of Q_0.

The estimated convective velocities u_f for heat transport are lower than for mass transport. Whereas the estimated dispersion coefficients D_f for heat transport are higher than for mass transport. Regarding the transfer rate coefficient α, it assumes very low values for mass transport relatively to the convective velocity. Instead for heat transport the exchange rate coefficient is of the same order of magnitude of the convective velocity and, considering a characteristic length equal to L = 0.601 m, the effect of dual – porosity is very strong and cannot be neglected relatively to the investigated injection flow range.

Both mass and heat transport show a satisfactory fitting. In particular manner, *RMSE* varies in the range 0.0015 – 0.0180 for mass transport and in the range 0.0030 – 0.236 for heat transport, whereas r^2 varies in the range 0.9863 – 0.9987 for mass transport and in the range 0.0963 – 0.9998 for heat transport.

In order to investigate the different behavior between mass and heat transport, the relationships between injection flow rate and the transport parameters have been analyzed. In Figure 5 the relationship between u_f and Q_0 is reported. Whereas in figures 6 and 7 are reported the dispersion coefficient D_f and the exchange term α as function of u_f. The figures show a very different behavior between mass and heat transport.

Regarding mass transport experiments according to previous studies (Cherubini at al., 2013 and 2014) the figure 5 shows that for values of Q_0 higher than 4×10^{-6} m^3s^{-1} u_f increases less rapidly. This behavior was due to the presence of inertial forces that gave rise to a retardation effect on solute transport.

Instead figure 6 shows a linear relationship between u_f and D_f suggesting that inertial forces didn't exert any effect on dispersion and that geometrical dispersion dominates the Aris – Taylor dispersion.

The estimated exchange rate coefficient α is much lower than the convective velocity. These results suggest that in the case study fracture – matrix exchange is very slow and it may not influence mass transport. Non Fickian behavior observed in the experimental BTCs is therefore dominated mainly by the presence of inertial forces and the parallel branches.

A very different behavior is observed for heat transport. Heat convective velocity doesn't seem to be influenced by the presence of the inertial force whereas u_f is influenced by fracture matrix exchange phenomena resulting in a significant retardation effect.

In the same way as for mass transport, for heat transfer a linear relationship is evident between dispersion and convective velocity. Even if heat convective velocity is lower than solute advective velocity, the longitudinal thermal dispersivity assumes higher values than the longitudinal solute dispersivity. Also for heat transport experiments a linear relationship between u_f and D_f has been found.

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Once the model parameters for each flow rate have been determined, the unit response function (f_{URF}), corresponding to the *PDF* obtained from impulsive injection of both solute and temperature tracers, is obtained. The unit response function can be characterized using the time moments and tail character analysis.

The mean residence time t_m assumes the following expression:

$$t_m = \frac{\int_0^\infty t f_{URF}(t)\,dt}{\int_0^\infty f_{URF}(t)\,dt} \tag{45}$$

Whereas the nth normalized central moment of distribution of the f_{URF} versus time can be written as:

$$\mu_n = \frac{\int_0^\infty (t-t_m)^n f_{URF}(t)\,dt}{\int_0^\infty f_{URF}(t)\,dt} \tag{46}$$

The second moment μ_2 can be used in order to evaluate the dispersion relative to t_m, whereas the skewness is a measure of the degree of asymmetry and it is defined as follows:

$$S = \mu_3 / \mu_2^{3/2} \tag{47}$$

The tailing character t_c can be described as:

$$t_c = \frac{\Delta t_{fall}}{\Delta t_{rise}} \tag{48}$$

Where Δt_{fall} denotes the duration of the falling limb defined as the time interval from the peak to the tail cutoff which is the time when the falling limb first reaches a value that is 0.05 times the peak value. Δt_{rise} is defined as the time interval from the first arrival to the peak. This quantity provides a measure of the asymmetry between the rising and falling limbs. A value of t_c significantly higher than 1 indicates an elongated tail compared to the rising limb (Cherubini et al., 2010b).

In Figure 8 is reported the mean travel time versus the injection flow rates. The figure highlights that t_m for heat transport is about 3 times higher than for mass transport. In particular way t_m varies in the range 40. 3 - 237.1 *s* for mass transport and in the range 147.8 – 506.9 *s* for heat transport. This result still highlights that heat transport is more delayed than mass transport.

In same way the skewness *S* (Figure 9) and tailing character t_c (Figure 10) are reported as function of Q_0.

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A different behavior for heat and mass transport is observed for the skewness coefficient. For heat transfer the skewness shows a growth trend which seems to decrease after $Q_0 = 3\times10^{-6}$ m^{3}s^{-1}. Its mean value is equal to 2.714. For solute transport the S does not show a trend, and assumes a mean value equal to 2.018.

The tailing character does not exhibit a trend for both mass and heat transport. In either cases t_c is significantly higher than 1, specifically 7.70 and 30.99 for mass and heat transport respectively.

In order to explain the transport dynamics, the trends of dimensionless numbers *Pe* and *Da* varying the injection flow rate have been investigated. The Figure 11 shows the *Pe* as function of Q_0 for both mass and heat experiments. As concerns mass experiments *Pe* increases as Q_0 increases, assuming a constant value for high values (Pe = 7.5) of Q_0. For heat transport a different behavior is observed, *Pe* showing a constant trend and being always lower than one. Even if the injection flow rate is relatively high, thermal dispersion is the dominating mechanism in heat transfer.

Figure 12 reports D_a as function of Q_0. For mass transport D_a assumes very low values, of the order of magnitude of 10^{-4}.

The convective transport scale is very low respect to the exchange transport scale, thus the mass transport in each single fracture can be represented with the classical advection dispersion model.

As regards heat transport D_a assumes values around the unit showing a downward trend as injection flow rate increases switching from higher to lower values than the unit. As injection flow rate increases the convective transport time scale reduces more rapidly than the exchange time scale.

These arguments can be explained because the relationships between Q_0 and u_f show a change of slope when D_a becomes lower than the unit. In other words when D_a is higher than the unit the exchange between fracture and matrix dominates on the convective transport giving rise to a more enhanced delay on heat transport, conversely when D_a is lower than one convective transport dominates on fracture- matrix interactions and the delay effect is reduced.

Furthermore this effect is evident also on the trend observed in the graph $S - Q_0$ (Figure 9). For values of D_a lower than the unit a change of slope is evident, the skewness coefficient increases more slowly. Thus for D_a>1 the early arrival and the tail effect of *BTC* increase more rapidly than for *Da*<1.

Note that even if D_a presents a downward trend as Q_0 increases, when the latter exceeds Q_{crit} a weak growth trend for D_a is detected, that however assumes values lower than the unit.

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The Figure 13 shows the dimensionless group $Pe \times D_a$ varying the injection flow rate. Regarding mass transport $P_e \times D_a$ is of the order of magnitude of 10^{-3} confirming the fact that the fracture – matrix interaction can be neglected relatively to the investigated range of injection flow rates. For heat transport $P_e \times D_a$ assumes values just below the unit, with a downward trend as Q_0 increases. t_d and t_e have the same order of magnitude.

In order to find the optimal conditions for heat transfer in the analyzed fractured medium the thermal power exchanged per unit temperature difference $\dot{Q}/\left(T_{inj}-T_0\right)$ ($ML^2T^{-1}K^{-1}$) for each injection flow rate in quasi steady state conditions can be estimated. The thermal power exchanged can be written as:

$$\dot{Q} = \rho C_p Q_0 \left(T_{inj} - T_{out}\right) \tag{49}$$

The outlet temperature T_{out} can be evaluated as function of the f_{URF} using the following expression:

$$T_{out} = T_0 + \left(T_{inj} - T_0\right)\int_0^{\infty} f_{URF}\left(t\right)dt \tag{50}$$

Substituting the Equation (50) in the Equation (49) the thermal power exchanged per unit temperature difference is:

$$\frac{Q}{\left(T_{inj}-T_0\right)} = \left(1 - \int_0^{\infty} f_{URF}\left(t\right)dt\right)\rho C_p Q_0 \tag{51}$$

Figure 14 shows the similarities between the relationship $\dot{Q}/\left(T_{inj}-T_0\right)$ - Q_0 (Figure 14 a) and Da – Q_0 (Figure 14 b). Higher Da values correspond to higher values of $\dot{Q}/\left(T_{inj}-T_0\right)$. The thermal power exchanged increases as the Damköhler number increases as shown in Figure 14c. These results highlight that for the observed case study the optimal condition for thermal exchange in the fractured medium is obtained when the exchange time scale is lower than the convective transport scale or rather when the dynamics of fracture – matrix exchange are dominant on the convective ones.

Moreover in a similar way to Da, $\dot{Q}/\left(T_{inj}-T_0\right)$ shows a weak growth trend when Q_0 exceeds Q_{crit}. This means that the nonlinear flow regime improves the fracture – matrix thermal exchange, however at high values of injection flow rates convective and dispersion time scales are less than the exchange time scale. Nevertheless these results have been observed in a small range of Da numbers close to the unit. In order to generalize these results a larger range of Da numbers should be investigated.

In order to estimate the effective thermal conductivity coefficient k_e, the principle of conservation of heat energy can be applied to the whole fractured medium. Neglecting the heat stored in the fractures,

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the difference between the heat measured at the inlet and at the outlet must be equal to the heat diffused into the matrix:

$$\rho C_p Q_0 \left(T_{inj} - T_{out}\right) = \int_{A_f} k_e \left.\frac{dT_m}{dz}\right|_{z=wf/2} dA_f \tag{52}$$

where A_f is the whole surface area of the whole active fracture network and the gradient of T_m can be evaluated according to Equation (16). Then the average effective thermal conductivity $\bar{k}_e$ can be obtained as:

$$\bar{k}_e = \frac{\rho C_p Q_0 \left(T_{inj} - T_{out}\right)}{\int_{A_f} k_e \left.\frac{dT}{dz}\right|_{z=wf/2} dA_f} \tag{53}$$

The average effective thermal conductivity has been estimated for each injection flow rate (Figure 15) and assumes a mean value equal to $\bar{k}_e = 0.1183\ \mathrm{Wm^{-1}K^{-1}}$. The estimated $\bar{k}_e$ is one order of magnitude lower than the thermal conductivity coefficient reported in the literature (Robertson, 1988). Fractured media have a lower capacity for diffusion as opposed to the Tang's model which has unlimited capacity. There is a solid thermal resistance in the fluid to solid heat transfer processes which depends on the rock – fracture size ratio.

This result is coherent with previous analyses on heat transfer carried out on the same rock sample (Pastore et al. 2015). In this study Pastore et al. (2015) found that the ENM model failed to model the behavior of heat transport in correspondence of parallel branches where the hypothesis of Tang's solution of single fracture embedded in a porous medium having unlimited capacity cannot be considered valid. In parallel branches the observed BTCs are characterized by less retardation of heat propagation as opposed to the simulated BTCs.

Conclusions

Aquifers offer a possibility of exploiting geothermal energy by withdrawing the heat from groundwater by means of a heat pump and subsequently supplying the water back into the aquifer through an injection well. In order to optimize the efficiency of the heat transfer system and minimize the environmental impacts it is necessary to study the behavior of convective heat transport especially in fractured media, where flow and heat transport processes are not well known.

Laboratory experiments on the observation of mass and heat transport in a fractured rock sample have been carried out in order to analyse the contribution of thermal dispersion in heat propagation processes, the contribution of nonlinear flow dynamics on the enhancement of thermal matrix diffusion and finally the optimal heat recovery and heat dissipation strategies.

The parameters that control mass and heat transport have been estimated using the ENM model based on Tang's solution.

Heat transport shows a very different behavior compared to mass transport. The estimated transport parameters show differences of several orders of magnitude. Convective thermal velocity is lower than solute velocity, whereas thermal dispersion is higher than solute dispersion, mass transfer rate assumes a very low value suggesting that fracture – matrix mass exchange can be neglected. Non - fickian behavior of observed solute BTCs is mainly due to the presence of the secondary path and nonlinear flow regime. Contrarily heat transfer rate is comparable with convective thermal velocity giving rise to a retardation effect on heat propagation in the fracture network.

The discrepancies detected in transport parameters are moreover observable through the time moment and tail character analysis which demonstrate that the dual porosity behavior is more evident in the thermal BTCs than in the solute BTCs.

The dimensionless analysis carried out on the transport parameters proves that as the injection flow rate increases thermal convection time scale decreases more rapidly than the thermal exchange time scale, explaining the reason why the relationship $Q_0 - u_f$ shows a change of slope for *Da* lower than the unit.

Thermal dispersion dominates heat transport dynamics, the Peclet number and the product between Peclet number and Damköhler number is almost always less than the unit.

The optimal conditions for thermal exchange in a fracture network have been investigated. The power exchanged increases in a potential way as *Da* increases in the observed range.

The rock – fracture size ratio plays an important role in the fluid to solid heat transfer processes. It represents a key parameter in order to design devices for heat recovery and head dissipation that exploit the convective heat transport in fractured media. The estimation of the average effective thermal conductivity coefficient shows that it is not efficient to store thermal energy in rocks with high fracture density because the fractures are surrounded by a matrix with more limited capacity for diffusion giving rise to an increase in solid thermal resistance.

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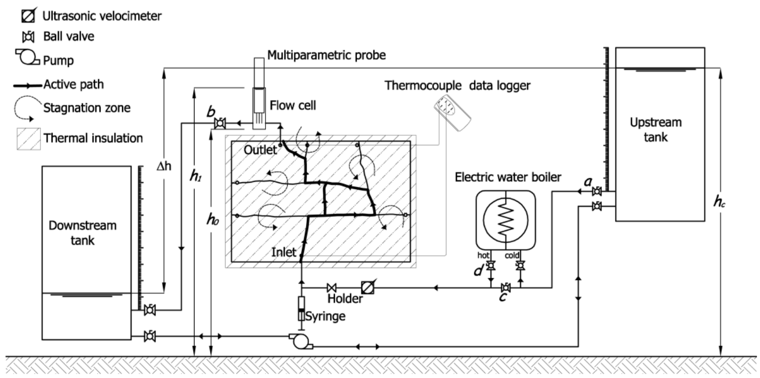

Figure 1. Schematic diagram of the experimental setup.

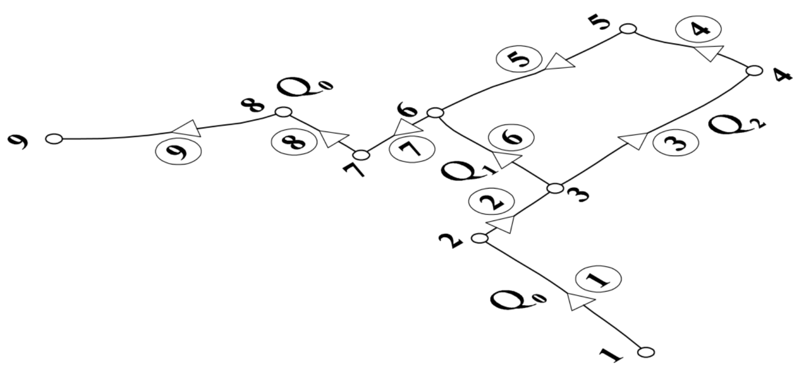

Figure 2. Two dimensional pipe network conceptualization of the fracture network.

Q_0 (m^3s^{-1})×10^{-6}	u_f (ms^{-1})×10^{-3}	D_f (ms^{-2})×10^{-3}	α (s^{-1})×10^{-6}	RMSE	r^2
1.319	4.38 ÷ 4.47	0.68 ÷ 0.70	4.80 ÷ 5.06	0.0053	0.9863
1.843	6.21 ÷ 6.28	0.57 ÷ 0.58	2.86 ÷ 3.01	0.0026	0.9954
2.234	6.54 ÷ 6.59	0.66 ÷ 0.67	3.09 ÷ 3.13	0.0017	0.9976
2.402	7.64 ÷ 7.68	0.67 ÷ 0.67	2.65 ÷ 2.68	0.0015	0.9983
2.598	9.88 ÷ 9.94	0.80 ÷ 0.82	2.76 ÷ 2.84	0.0015	0.9987
2.731	8.27 ÷ 8.35	0.75 ÷ 0.76	2.80 ÷ 2.91	0.0018	0.9977
2.766	8.35 ÷ 8.41	0.84 ÷ 0.85	2.65 ÷ 2.69	0.0021	0.9978
3.076	11.33 ÷ 11.43	0.89 ÷ 0.91	2.53 ÷ 2.59	0.0029	0.9982
3.084	10.86 ÷ 10.95	0.87 ÷ 0.89	3.11 ÷ 3.18	0.0022	0.9982

4.074	15.88 ÷ 16.02	1.19 ÷ 1.21	2.89 ÷ 2.94	0.0048	0.9979
4.087	15.07 ÷ 15.20	1.11 ÷ 1.13	3.75 ÷ 3.83	0.0045	0.9976
4.132	14.71 ÷ 14.82	1.08 ÷ 1.09	2.93 ÷ 2.98	0.0028	0.9985
4.354	15.63 ÷ 15.77	1.14 ÷ 1.16	3.24 ÷ 3.30	0.0052	0.9979
4.529	17.05 ÷ 17.21	1.30 ÷ 1.32	2.88 ÷ 2.94	0.0055	0.9978
5.852	19.26 ÷ 19.38	1.44 ÷ 1.46	4.21 ÷ 4.25	0.0042	0.9983
5.895	19.38 ÷ 19.54	1.37 ÷ 1.39	3.77 ÷ 3.82	0.0058	0.9981
6.168	18.98 ÷ 19.17	1.36 ÷ 1.39	2.87 ÷ 2.92	0.0091	0.9973
7.076	20.64 ÷ 20.86	1.36 ÷ 1.39	3.33 ÷ 3.39	0.0123	0.9963
7.620	20.47 ÷ 20.75	1.52 ÷ 1.55	2.33 ÷ 2.39	0.0180	0.9951
7.983	21.33 ÷ 21.58	1.61 ÷ 1.64	2.92 ÷ 2.98	0.0137	0.9965
8.345	21.71 ÷ 21.97	1.65 ÷ 1.68	2.81 ÷ 2.86	0.0136	0.9964

Table 1. Estimated values of parameters, RMSE, and determination coefficient r^2 for ENM with Tang's solution at different injection flow rates for mass transport.

Q_0 (m^3s^{-1})$\times10^{-6}$	u_f (ms^{-1})$\times10^{-3}$	D_f (ms^{-2})$\times10^{-3}$	α (s^{-1})$\times10^{-3}$	RMSE	r^2
1.835	2.20 ÷ 2.91	1.91 ÷ 1.95	6.27 ÷ 6.59	0.0065	0.9997
2.325	1.74 ÷ 2.73	1.82 ÷ 1.91	5.39 ÷ 9.26	0.0098	0.9992
2.462	0.35 ÷ 0.52	2.42 ÷ 2.57	2.25 ÷ 2.33	0.0138	0.9984
2.605	0.44 ÷ 0.54	2.33 ÷ 2.40	0.74 ÷ 0.77	0.0073	0.9995
2.680	2.18 ÷ 2.95	1.77 ÷ 1.83	5.68 ÷ 8.31	0.0030	0.9998
2.800	0.36 ÷ 0.79	2.53 ÷ 2.68	3.54 ÷ 3.72	0.0213	0.9982
2.847	1.73 ÷ 3.16	1.98 ÷ 2.06	4.95 ÷ 13.45	0.0283	0.9978
3.003	2.34 ÷ 2.87	2.24 ÷ 2.32	5.33 ÷ 6.55	0.0033	0.9998
3.998	2.56 ÷ 2.75	6.63 ÷ 6.80	2.05 ÷ 2.11	0.0150	0.9993
4.030	2.60 ÷ 2.83	7.18 ÷ 7.36	1.42 ÷ 1.52	0.0147	0.9993
4.217	3.85 ÷ 4.56	8.92 ÷ 9.29	4.86 ÷ 5.77	0.0228	0.9945
4.225	2.43 ÷ 2.64	7.53 ÷ 7.84	1.64 ÷ 1.80	0.0251	0.9987
4.471	2.30 ÷ 3.13	9.18 ÷ 9.50	1.06 ÷ 1.33	0.1115	0.9957
5.837	3.51 ÷ 4.13	4.95 ÷ 5.36	0.61 ÷ 0.79	0.2360	0.9872
5.880	2.71 ÷ 3.10	4.23 ÷ 4.60	0.04 ÷ 0.05	0.1997	0.9926
6.445	4.71 ÷ 5.12	6.18 ÷ 6.81	1.49 ÷ 1.54	0.2156	0.9863
7.056	8.15 ÷ 8.46	10.05 ÷ 10.74	5.63 ÷ 6.00	0.0694	0.9951
7.959	9.64 ÷ 10.11	18.40 ÷ 19.47	10.92 ÷ 11.55	0.0662	0.9971
8.971	13.40 ÷ 13.79	24.57 ÷ 25.82	15.35 ÷ 15.85	0.0303	0.9985
12.364	11.01 ÷ 11.67	21.97 ÷ 22.63	5.23 ÷ 5.25	0.0631	0.9939
12.595	13.71 ÷ 14.26	26.65 ÷ 27.61	9.26 ÷ 9.41	0.0426	0.9955

Table 2. Estimated values of parameters, RMSE, and determination coefficient r^2 for ENM with Tang's solution at different injection flow rates for heat transport.

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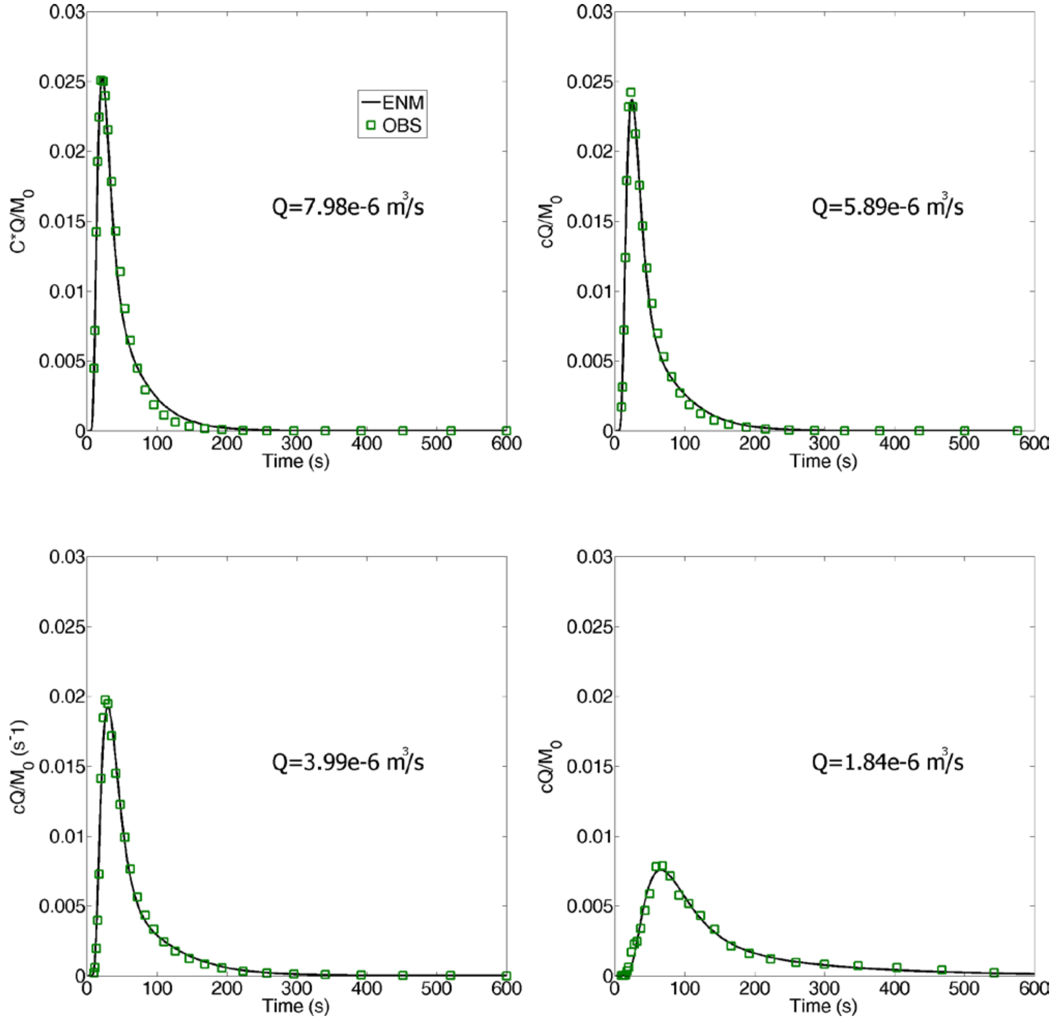

Figure 3. Fitting of BTCs at different injection flow rates using ENM with Tang's solution for mass transport.

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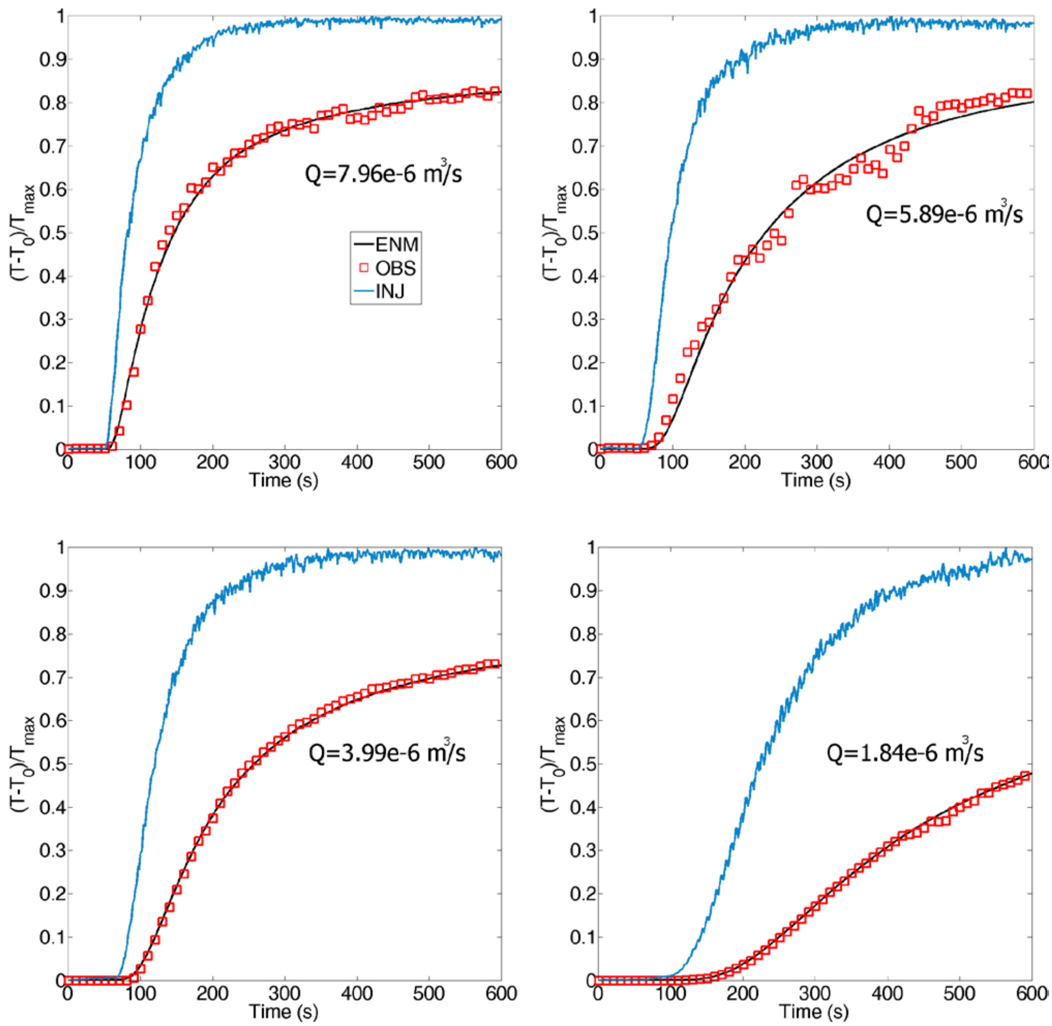

Figure 4. Fitting of BTCs at different injection flow rates using ENM with Tang's solution for heat transport.

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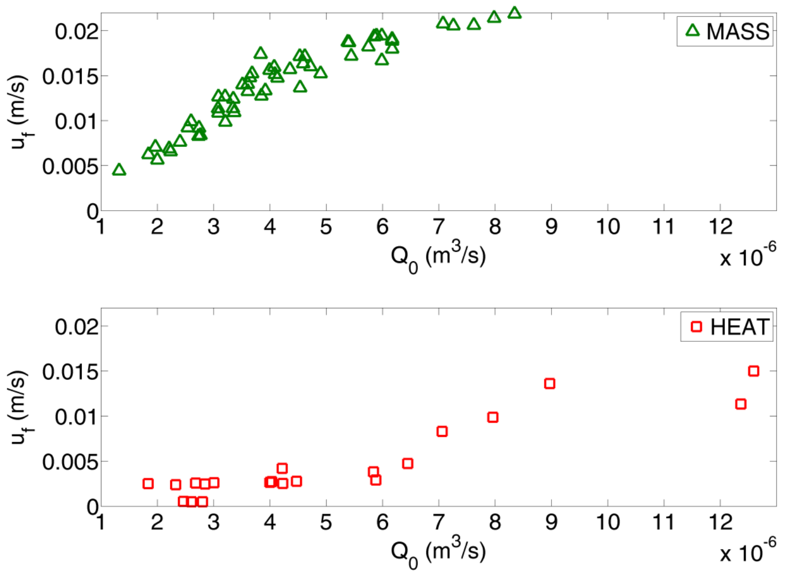

Figure 5. Velocity u_f (m s^{-1}) as function of the injection flow rate Q_0 (m3s $^{-1}$) for ENM with Tang's solution for both mass and heat transport.

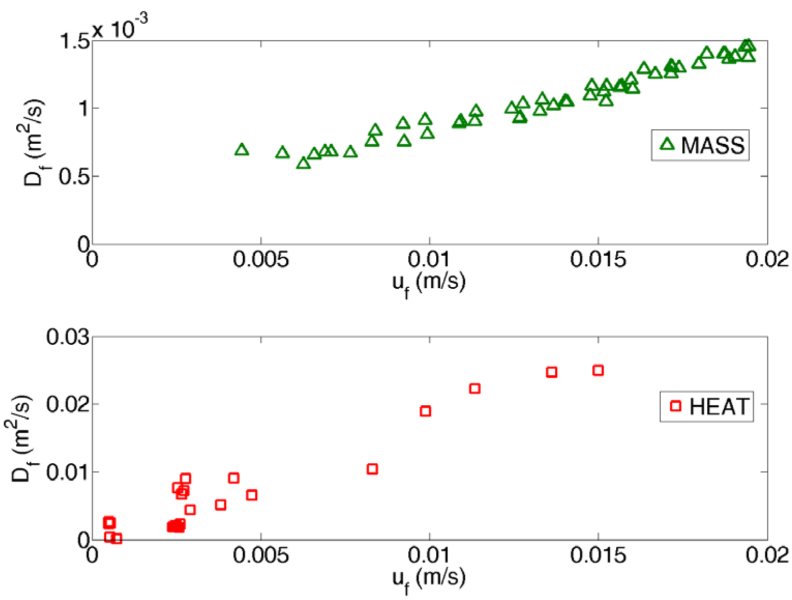

Figure 6. Dispersion D_f (m s^{-2}) as function of velocity u_f (m s^{-1}) for ENM with Tang's solution for both mass and heat transport.

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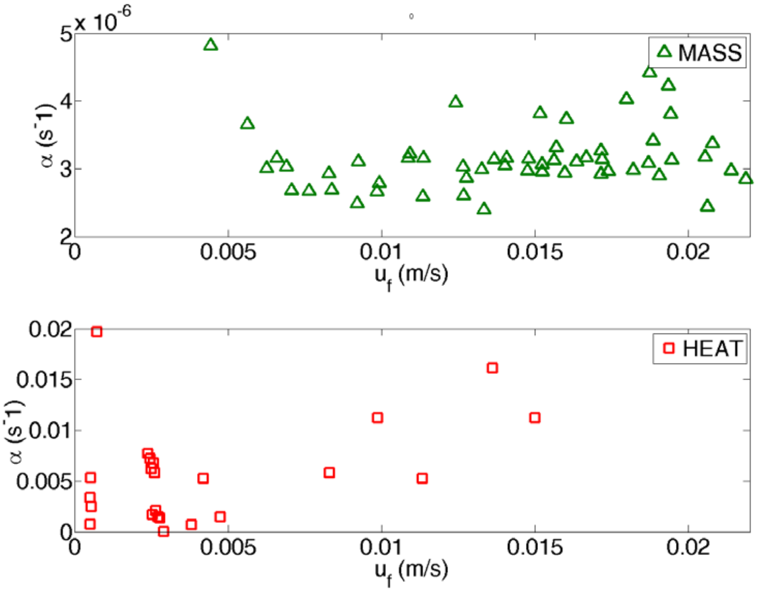

Figure 7. Transfer coefficient α (s^{-1}) as function of velocity u_f (ms^{-1}) for both mass and heat transport.

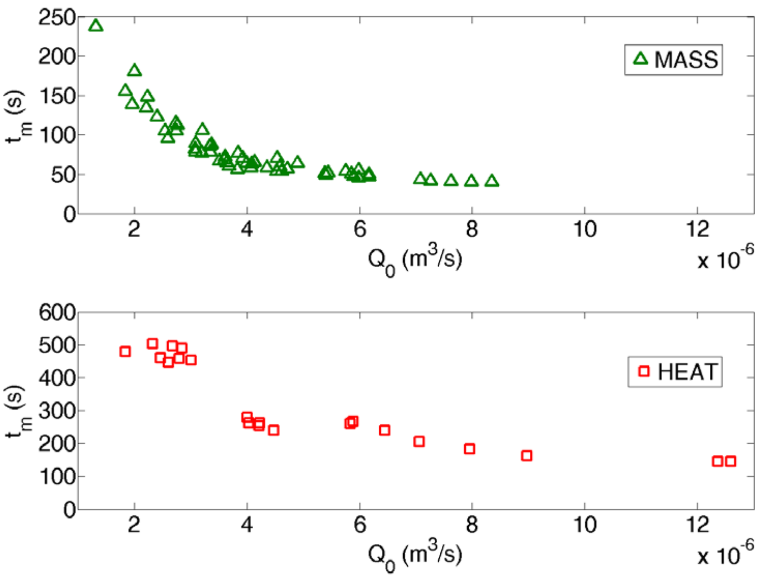

Figure 8. Mean travel time t_m (s) as function of injection flow rate for both mass and heat transport.

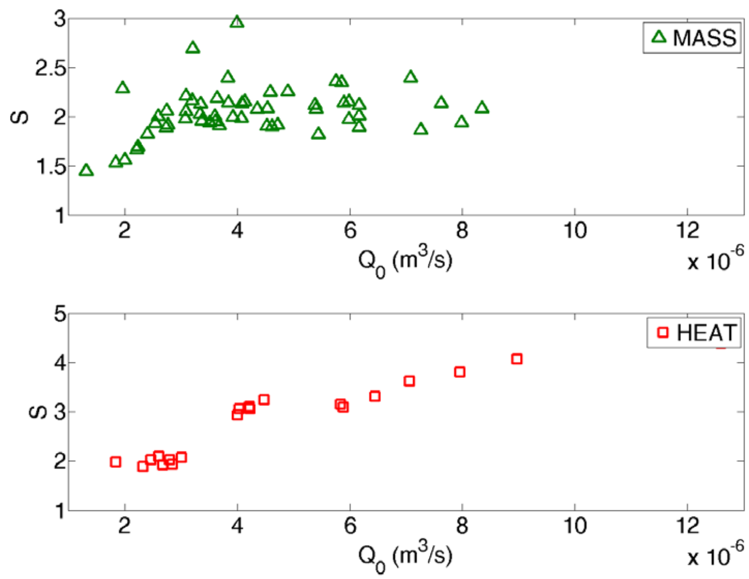

Figure 9. Skewness as function of injection flow rate for both mass and heat transport.

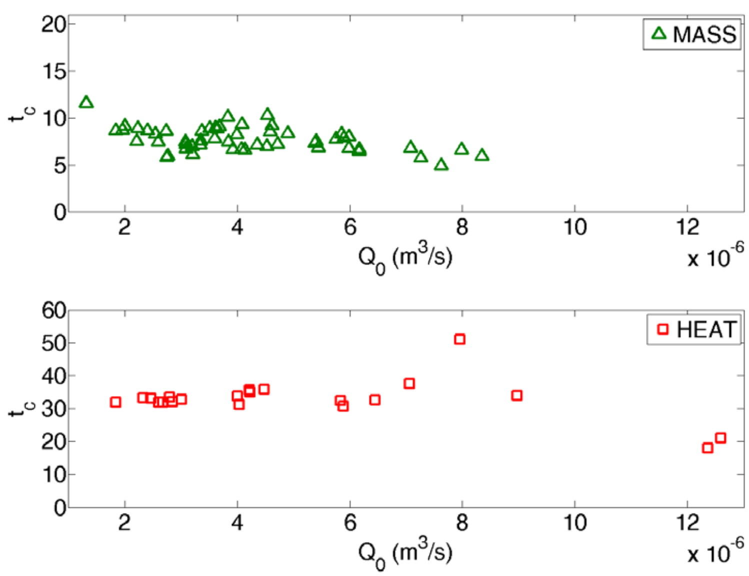

Figure 10. Tailing character t_c as function of injection flow rate for both mass and heat transport.

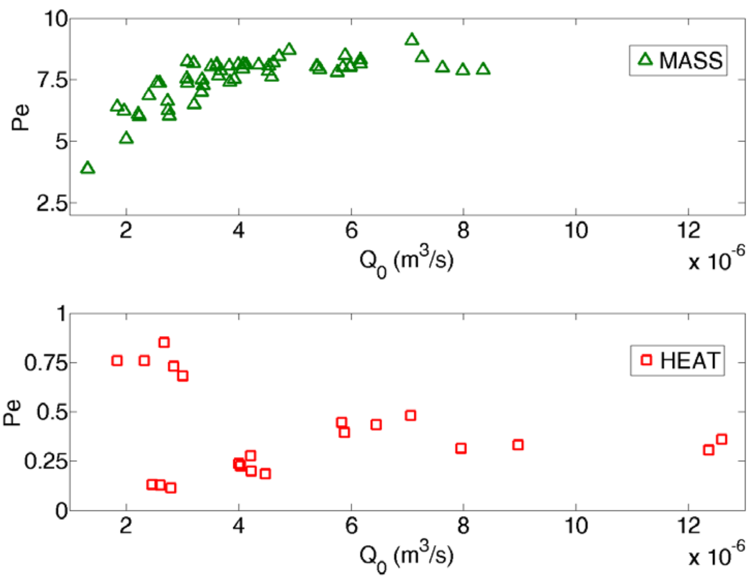

Figure 11. Peclet number as function of injection flow rate Q_0 (m^3s^{-1}) for both mass and heat transport.

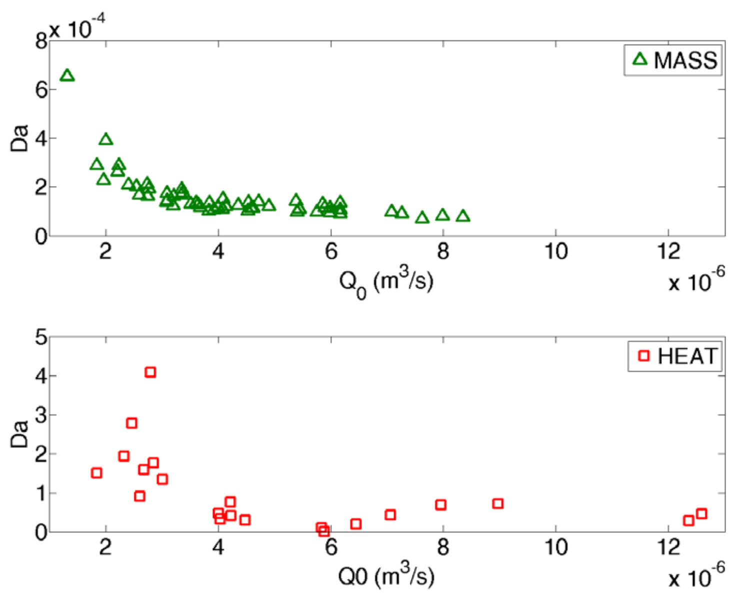

Figure 12. Da number as function of injection flow rate Q_0 (m^3s^{-1}) for both mass and heat transport.

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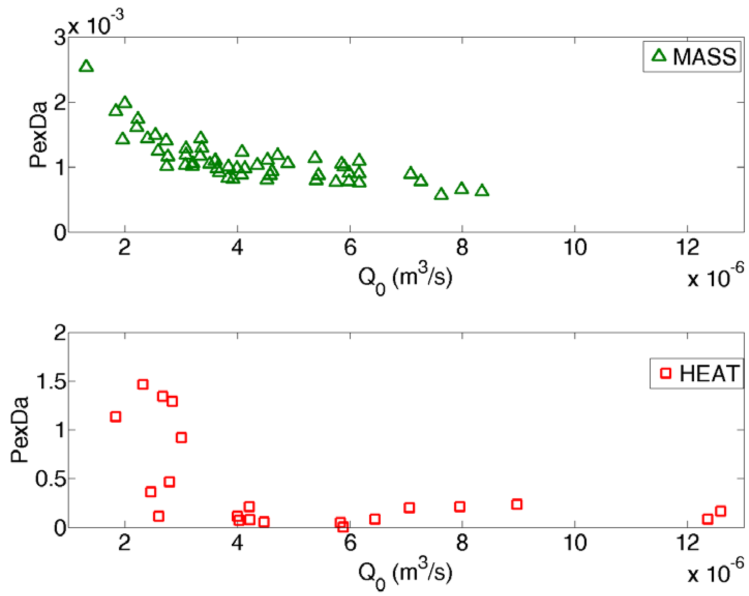

Figure 13. Pe×Da number as function of injection flow rate Q_0 (m^3s^{-1}) for both mass and heat transport.

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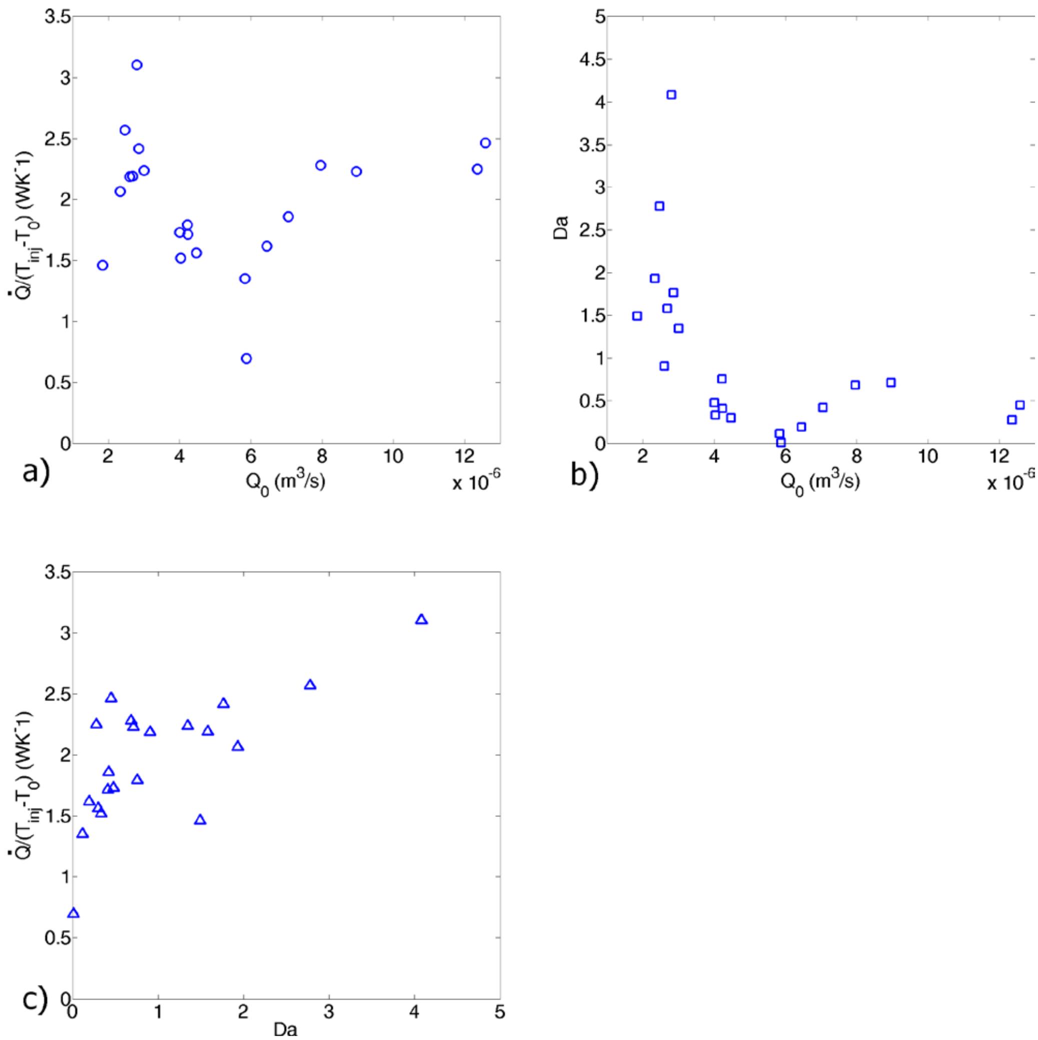

Figure 14. Heat power exchanged per difference temperature unit $\dot{Q}/(T_{inj}-T_0)$ as function of injection flow rate Q_0 (m^3s^{-1}) (a), Damköhler number *Da* as function of injection flow rate (b), power exchanged per difference temperature unit as function of Damköhler number (c).

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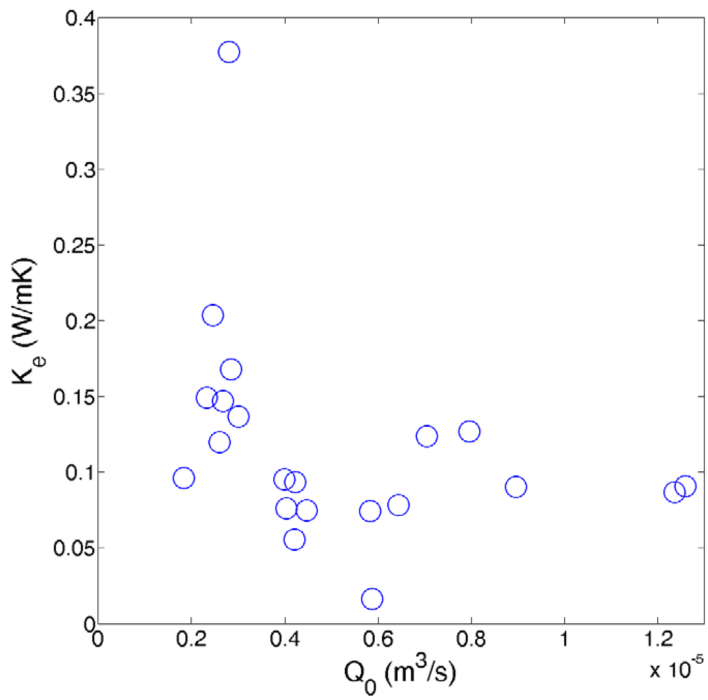

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743 **Figure 15. Effective thermal conductivity k_e ($Wm^{-1}K^{-1}$) as function of injection flow rate Q_0 (m^3s^{-1}).**