We thank Giacomo Medici, Quanrong Wang, Toshiyuki Bandai and an anonymous reviewer, for the time and the comments, which helped to improve our manuscript. We considered all of the comments carefully and applied changes in our manuscript. To highlight the nature of our replies we use a traffic light system indicating agreement with the reviewer marked in <mark style="background-color:green">green</mark>, partial agreement in <mark style="background-color:yellow">yellow</mark> and objections in <mark style="background-color:red">red</mark>. Our responses and the changes made in our manuscript are written in blue. The line number refers to the line in the track-changes version of the revised manuscript.

Response to Community Comments 1

General comments

Good theoretical research that can be improved addressing the specific comments below.

Thank you for your effort in reading our work and providing constructive comments. We have considered your comments carefully and incorporated further clarifications on the revised manuscript. Please find our detailed replies below.

Specific comments

Line 23 "Accurately describing heat transport in porous media has long been a focus in both engineering and science". Insert recent review papers on heat transport in geological media since the sentence is not backed-up by references.

- Review of discrete fracture network characterization for geothermal energy extraction. Frontiers in Earth Science, 11, p.1328397

- Review of geothermal energy resources, development, and applications in China: Current status and prospects. Energy, 93, pp.466-483

Thank you for your suggestions. <mark style="background-color:yellow">We partially agree.</mark> As the sentence misses a citation, we included the suggested review paper by Zhu et al. (2015), which provides a review of applications of geothermal energy systems. However, we did not include the first suggested review paper (Medici et al., 2023), as it contains a topic that is beyond our scope. Since our study focuses on heat transport in unconsolidated and non-fractured porous aquifers, the reference regarding heat transport in fractured aquifers is not appropriate.

Hence, we revised the sentence including the references in line 28:

"Accurately describing heat transport in porous media has long been a focus in both engineering and science (e.g., Stallman,1965; Nield and Bejan, 2017; Zhu et al., 2015)."

Line 27. Specify low enthalpy geothermal systems?

<mark style="background-color:green">We agree</mark> that this needs further clarification. We have therefore revised the sentence in our manuscript in lines 32-33:

"Understanding how heat propagates through sedimentary aquifers is also crucial for modeling thermal responses and designing sustainable geothermal systems, which utilize groundwater, such as groundwater heat pump (GWHP) and aquifer thermal energy storage (ATES) systems."

Line 78. The aim is clear, but please specify the 3 to 4 objectives of your research by using numbers (e.g., i, ii and iii).

We agree that objectives of our research need specification and have revised the sentences in lines 83-88:

> "In this study, we present 1) an advanced laboratory experiment to investigate granular-scale heat transport by measuring temperature responses in fluid and solid phases, using varying grain sizes (5 - 30 mm) and flow velocities (3 - 23 m d^{-1}) under step-like temperature changes. 2) analysis of experimental data to elucidate the influence of grain size and flow velocity on heat transport in porous media, evaluating the presence of LTNE effects. 3) interpretation of the experimental results using heat transport models, with two-phase heat transport described by standard models in the literature."

Line 153. "Porous media" provide more detail on the material that you used to create the porous material that approximate the geological media in your analogue.

We agree that the term, "porous media", has to be further clarified. The porous media used for the experiments comprises of packed glass beads in a vertical column, as is shown in Fig. 1. The porous media in this study therefore represents unconsolidated granular porous media.

We revised the sentence including the information in line 172:

> "To describe heat transport during flow through porous media representing an unconsolidated aquifer, the one-phase advection-diffusion heat transport equation is generally used in hydrogeological applications (Heinze, 2024)."

Lines 308-424. Provide more detail on the validity of your analogue experiment that is at small scale. Much smaller than the aquifer. This point can be addressed here or in the introduction.

We agree that the validity of our experiments at small scale has to be further discussed in the context of hydrogeology. While LTNE effects have been reported in the field of Earth Science, understanding LTNE effects starts from the grain scale. In our study, LTNE effects were experimentally determined at the granular scale by measuring fluid and solid phases separately. The implications of two-phase heat transport on the large scale can be inferred from our experimental findings.

A new paragraph is therefore added to the discussion of the revised manuscript (lines 483-486):

> "Our study directly measures thermal disequilibrium between fluid and solid phases (i.e., LTNE effects) at the granular scale, offering insights into the conditions under which LTNE effects arise and may impact larger scale. However, further research is needed to connect findings from the grain scale to field-scale applications."

Lines 308-424. Provide more detail on the validity of your analogue research taking into account that porous aquifers (typically siliciclastic) are very heterogeneous. This point can be done here or in the introduction.

We agree that a further discussion on heterogeneous porous aquifer is required. The experiments in this study aimed to evaluate LTNE effects for different grain sizes and flow velocities. Although the relation

between LTNE effects and each grain size was revealed in this study, this finding contributes fundamental knowledge for future research that can look at LTNE effects in heterogeneous porous media.

A discussion is therefore added in line 486-489:

"This heat transport experiments focused on the influence of grain size and flow velocity on LTNE, addressing a critical gap in the scientific literature. While our results are representative for porous media with uniform grain sizes, future research should investigate LTNE effects in porous media with realistic grain size distributions."

Figures

Figure 1a. Insert the spatial scale.

We chose not to add a spatial scale on Fig. 1a, as it was designed to illustrate all components of our experimental setup without strict adherence to real scale, allowing for a more space-efficient layout. While the dimension of the porous media column and the relative size of other components are accurately represented, the spacing between each component does not reflect actual distances.

Figure 1d. Insert the spatial scale.

We agree that Fig. 1d requires a scale bar. To clarify the scale in the other subfigures, a scale bar was also included in Fig. 1b and Fig. 1c.

We revised Fig.1b-d on line 122.

Figures 3, 5 and 8. Room to make the figures larger.

We agree and have therefore enlarged the figures in our revised manuscript.

Response to Reviewer Comments 1

To investigate the presence of local thermal non-equilibrium (LTNE) effects during heat flow in porous media, in the present work, laboratory experiments systematically investigated heat transport by exposing water flow to temperature step inputs. The experiments were conducted at Darcy velocities ranging from 3 to 23 m/d through porous media comprising idealized spherical grains with diameters between 5 and 30 mm. This work is new and interesting, I think this paper can do well in the future. I have a few specific comments that I will list below in order to improve the current manuscript.

Thank you for pointing out the key messages and seeing the positive prospective in our manuscript. We considered all of your recommendations to improve our manuscript. Please find a detailed reply to each of your comments below.

Lines 68-74: Yes, there are very few experimental studies on LTNE in porous media, and in addition to the two studies mentioned by the authors, laboratory experimental studies have been conducted in the study of Shi et al. (2024) [DOI:10.1029/2024WR037382], and it is suggested that the authors refer to their experimental studies section for an introduction as well.

We agree that Shi et al. (2024) has to be included as an experimental study and have revised the manuscript as follows (lines 77-78):

> "Shi et al. (2024) suggested new LTNE criteria based on experimental validation, demonstrating that LTNE effects can also occur for large grain sizes >10 mm with flow velocities <2 m d^{-1}."

Line 163: "thermal conductivity" -> "thermal conductivities"

We agree with the correction and revised the sentence in line 181:

> "λ_f and λ_s are the thermal conductivities of the fluid and solid, respectively."

Line 165: "specific heat capacity" -> "specific heat capacities"

We agree with the correction and revised the sentence in the manuscript in line 184:

> "c_f and c_s are the specific heat capacities of the fluid and solid (J kg^{-1} K^{-1}), respectively."

Line 173: "dispersion coefficient" should be changed to "thermal dispersion coefficient" as "dispersion coefficient" is a part of "thermal dispersion coefficient".

We agree with the correction and revised our manuscript in line 193:

> "We note that the thermal dispersion coefficient D in this model incorporates both thermal diffusion through the two phases as well as and hydrodynamic dispersion resulting from the flow through tortuous flow paths."

Eq. (14): Heinze (2024) [DOI: 10.1016/j.earscirev.2024.104730] provides a detailed overview of this relationship, and I would suggest that the authors could make appropriate references to the work of Heinze (2024) here. Just a suggestion:)

We agree that the work by Heinze (2024) needs to be included.

We revised the sentence in line 212-214:

> "While previous studies suggested different *Nusselt* number correlations from mechanical engineering, Gossler et al. (2020) proposed a general form of *Nusselt* number correlation considering aquifer properties (Heinze, 2024). They suggested a correlation based on an adaptation of the *Nusselt* number by keeping the *Prandtl* number, a dimensionless parameter in the correlation of Wakao et al. (1979), constant for water at a fixed temperature."

Line 321: "In the study by Bandai et al. (2017), they revealed…"-> "Bandai et al. (2017) revealed…".

We agree with your suggestion and have revised the sentence in line 356:

> "Bandai et al. (2017) revealed the influence of particle size on thermal dispersion by heat transport experiments with small glass spheres (0.4 mm, 1 mm and 5 mm)."

Lines 412-413: Please express this sentence in two sentences.

We agree and have therefore revised this sentence in line 468-469 as suggested:

> "Our experimental results are interpreted by using standard analytical and numerical models accepted in the literature. These models are commonly applied to explain heat transport in groundwater and to gain insight into thermal properties and processes."

Response to Reviewer Comments 2

The manuscript presents novel heat transport/heat transfer experiments that address a long-standing research gap on the relevance of LTNE effects in aquifer systems. The manuscript is a highly valuable contribution to the research topic and provides great insights into the microscopic temperature distribution in large grain size sediments, building on previous experiments by some of the authors.

Thank you for your positive comments pointing out the value of our research. All of your comments were considered carefully to improve our manuscript. Our detailed replies and actions taken are provided below each of your comments.

Abstract: It would be great if the abstract could include some more quantitative values and clarifications. Examples:

- "some temperature differences were negative" -> the reader doesn't know what positive/negative temperature differences mean at this point.

Thank you for your suggestion. We agree that clarification is needed. When temperature difference between fluid and solid phases is computed over a time series, it typically forms a curve with a peak, reflecting the delayed thermal arrival in solid phase. However, some LTNE probe replicas showed an earlier thermal arrival in the solid phase, resulting in negative temperature difference. This suggests non-uniform flow, likely due to spatial variation in flow field at the same depth. Further details are provided in section 3.3 and 4.1.

We revised the sentence including this information in lines 12-14:

> "Surprisingly, the temperature differences between fluid and solid phases at the same depth were inconsistent, indicating non-uniform heat propagation likely caused by spatial variations of the flow field."

- "relatively good agreement", "became too significant" -> can these statements be quantified?

We agree and have therefore revised this in lines 15-20 providing quantifiers:

> "The fluid temperature simulated by the LTE and LTNE models for small grain sizes (5 mm-15 mm) showed similar fits to the experimental data, with the RMSE values differing by less than 0.01. However, for larger grain sizes (20 mm-30 mm), the temperature difference between fluid and solid phases exceeded 5 % of the system's temperature gradient at flow velocities ≥ 17 m d^{-1}, which falls outside the criteria for the LTE assumption."

- I believe that the term "magnitude of LTNE" is not universally known, given the wide readership of HESS. Therefore, I propose to define the term if it is used in the abstract.

We agree to clarify this term used in abstract and revised the sentence in line 21:

> "Additionally, for larger grain sizes (>20 mm), the LTNE model failed to predict the magnitude of LTNE (i.e., temperature difference between fluid and solid phase in time series) for all tested flow velocities due to experimental conditions being inadequately represented by the 1D model with ideal step input."

Materials and methods

The authors state at the beginning that "specialised experimental instrumentation" was used, but it remains unclear in the rest of the text what this "specialised instrumentation" is and how the current procedure was "adapted" from Gossler et al. (2019). The lessons learned from Gossler et al. (2019) are nicely highlighted in the following paragraphs.

We agree that the comparison between our experimental setup and the original one can be further explained. We have therefore added the following sentences in line 96-98:

> "Compared to the original setup by Gossler et al. (2019), only one refrigerated bath circulator was used to prepare water with a contrasting temperature as a heat source. Crucially, the measurement points were designed to allow separate temperature sensing in the fluid and solid phases."

Why were all samples measured in one experimental setup and stacked on top of each other? Why not test all grain sizes separately? Did the authors reverse the order of the spheres to check for a possible influence?

We agree that the arrangement of LTNE probes with different sizes requires further clarification and have included an explanation to the discussion of our revised manuscript (lines 391-399):

> "The experimental data was generated using specially designed setup to examine the influence of varying grain sizes on heat transport under different flow conditions. Drawing on insights from prior studies (Rau et al., 2012a; Gossler et al., 2019; Bandai et al., 2023), we crafted our setup to effectively measure the temperature difference between fluid and solid phases. This setup allows for efficient experimentation with two degrees of freedom (grain size and velocity) within a single configuration. By incorporating all six different grain sizes into one experiment, we were able to test identical flow velocities across different grain sizes, which is challenging to achieve in separate experiments. The grain sizes were arranged in increasing order along the depth of the column because of the evolution of the thermal front. Since the steepness of the thermal front decreases as heat moves downward, the smallest grain size, which is expected to exhibit smaller LTNE effects (Gossler et al., 2019), was placed at the top where the gradient is steepest and progressively the larger grain sizes positioned at greater depths."

We hope that this explanation clarifies the reviewer's concerns.

When filling the layers with the small glass beads, was it necessary to keep the outer PT100 free from contact with the smaller beads or did the authors rely on a (rapid) LTE between the small glass beads and water?

We agree that the description on the temperature measurement in the fluid phase is missing. The LTNE probes were designed with an assumption that the small glass beads with 1 mm diameter establish instant thermal equilibrium as justified by previous research (e.g., Gossler et al., 2020).

We have added the following to our revised manuscript to clarify this (lines 123-127):

> "Pt100 sensors for the fluid phase are embedded directly within small glass beads, without additional structure to separate them. While this setup may allow contact between the sensors and the beads, we assume that the fluid phase and solid phases of the small glass beads (dp = 1 mm) reach an instantaneous thermal equilibrium (LTE), resulting in identical temperatures. This design relies on the rapid thermal equilibrium established between the glass beads and water which is justified by previous research (e.g., Gossler et al., 2020)."

Analysis/Results

* What effect did the "correction" steps (pp. 225-229) have on the results? What was the difference/spread between the sensors? Should this be shown in Fig. 3? The curves in Fig. 3 are almost indistinguishable visually. In particular, which would be of interest, it is not possible to see whether the difference between Ts and Tf is consistent but shifted across the probes. Was there a systematic relationship between the spread and grain size or flow velocity? I would encourage the authors to try a different way of visualising Figure 3, perhaps adjusting the range of the x-axis or visualising differences rather than absolute values.

The correction method initially demonstrated temperature rise from the starting temperature. However, considering this feedback and a related comment from another reviewer (RC3), we have recognized and agreed that this correction might cause confusion for readers. Consequently, the experimental results have been analysed using normalized temperature values. Therefore, we have deleted the sentence for the previous correction method in our manuscript (lines 250 & 254-255).

We also agree that BTCs in Fig. 3 were challenging to distinguish and revised the Fig.3 by narrowing the x-axis range, making each BTC more discernible (line 295).

Regarding the difference/spread between the sensors, it seems to be attributed to the different local thermal velocities for each LTNE probe. It is also shown in a previous study by Bandai et al. (2023) with flow-through heat transport experiments in granular porous media.

* The wording in the text and figures does not seem to be consistent throughout the text. For example, Figure 2 refers to "calibrated temperature", which is not used in the text. Also, "inner" and "outer" Tf measurements are not explained in the text (Fig. 3) - could this be done in Fig. 1?

We agree that the legend in Fig. 3 is inconsistent compared to the one in other Figures.

We revised Fig. 3 indicating the two different pairs within each LTNE probe by number, e.g. Replica 1-1.

* The relevance of the negative temperature pulses is difficult to assess. l. 267f states: "was observed in some pairs of (...) measurements over all (...) flow velocities". What does this mean? Some replicates showed negative temperature pulses while others showed positive pulses? Because this is associated with the smallest grain sizes: Could this be an experimental problem, as the Pt100 sensor is the same size for all grain sizes, so its placement within the glass beads is more sensitive in smaller beads? Also, l. 270: "both sides of the grain" suggests that there is a discrepancy between the Pt100 sensors to the left and right of the glass beads. This would be interesting to see rather than Fig 5a,c,e which shows pretty much two lines on top of each other. Does this grain size discrepancy only occur for the small grains or is it only of less significance for the larger glass beads? Is this what you want to show in Fig. 3?

We agree that the assessment of the inverse pulse requires further clarification, and therefore Fig.5 needs revision. The statement in line 267 of the preprint was intended to explain that the temperature difference between fluid and solid phases from LTNE probe replicas did not always result in a positive pulse, which would typically be expected due to the delayed thermal response in the solid phase. This phenomenon can be attributed to the non-uniform flow. The results with small grains can be strongly affected by the non-uniform flow due to the smaller representative elementary volume (REV) as stated in section 4.1 (lines 375-377).

We have therefore replaced Fig. 5 with a new version that presents ΔT measured on the left and right sides of a single sphere. This updated figure demonstrates the discrepancies in ΔT between the two sides of the glass sphere and how these patterns change under different flow velocities.

The new version of Fig. 5 replaced the previous version with edited figure caption in line 327.

Discussion

* Can the "agreement" between numerical models and experiments be quantified in some way to quantitatively demonstrate the "better fit"?

We agree that quantification of fitting is required and have revised the corresponding sentences to include the root mean squared error (RMSE) in the revised manuscript (line 502-506):

> "The LTE and LTNE model exhibit relatively good agreement with the breakthrough curves (BTCs) observed in the fluid phase for small grain sizes ranging from 5 to 15 mm, demonstrated by RMSE < 0.01. However, for larger grain sizes ($\geq$ 20 mm), the LTE model fails to adequately describe heat transport, primarily due to significant LTNE effects with $\Delta T(t)$ larger than 5 % of the system temperature gradient, violating LTE criteria as defined in section 3.3 and Fig. 7."

* The authors measure the temperature in the middle of the glass beads and refer to it as "solid temperature". However, within the glass beads there will be a radial thermal gradient. The "mean solid temperature" across the glass beads might be higher than the temperature measured observed by the authors. Hence, the heat transport within the larger grains takes longer time due to the larger distance from the outside of the glass bead to the temperature sensor. At the contact surface of the grain and the water, there still might be thermal equilibrium. While the subsequent theoretical considerations in terms of the influence of flow velocity go beyond the scope of this work, a short discussion on the scale effect could enrich the Discussion section.

We agree that an improved description on the solid temperature measurement should be included and have added the following in lines 399-405:

> "At each depth, the solid phase temperature for four LTNE probe replicas was measured at the center of the glass spheres to represent solid temperature. Measuring temperature at the surface of the glass spheres was technically challenging due to the sensor's thickness and the limited contact area with each sphere. Similar challenges and inconsistencies in surface temperature measurement for the solid phase were reported by Bandai et al. (2023) in their heat transport experiments. Therefore, this study assumes that the temperature at the center of the spheres accurately represents the solid phase temperature, disregarding any internal temperature gradient within the spheres."

Response to Reviewer Comments 3

The paper "Laboratory heat transport experiments reveal grain size and flow velocity dependent local thermal non-equilibrium effects" conducted laboratory experiments to clarify thermal non-equilibrium between solid and liquid phases in saturated porous media under forced convection. This study provides valuable laboratory experimental data on the effects of grain size and flow rates on thermal non-equilibrium between solid and fluid phases of saturated porous media. The authors measured not only the fluid temperature but also the temperature of solid phase by specifically designed probes, which only a few studies have reported before.

Regardless of the value of the experimental data, I have a few concerns regarding data analysis and interpretation of the experimental data. I believe the manuscript could be improved by re-analyzing the same data without additional experiments. Therefore, I recommend a major revision for potential publication of this manuscript.

Thank you for your detailed review which has brought up good questions. We considered all of your comments carefully to improve our manuscript. Please find our replies and revisions below each comment.

Major and minor points are summarized below (numbers indicate the line numbers).

Major points

Choice of LTNE model

While the authors used the LTNE model (Eq. 10 and Eq. 11), this LTNE model may not be applicable to the experimental data. The LTNE model with spatially uniform parameters (e.g., h_sf and lambda_s, eff) assumes that the physical property of solid phase is uniform in the spatial domain. However, in the experimental setup, glass spherical particles with varying sizes were embedded in finer glass spheres of 1 mm diameter. Although some of the parameters can be justified to be spatially uniform even in this setting (e.g., thermal conductivity of solid and porosity), this setting violates the assumption of the LTNE model. For example, the heat transfer coefficient and surface area are functions of grain sizes. The LTNE model with spatially uniform parameters is applicable when the porous media is made up of uniform grain sizes (could be non-uniform up to the validity of representative elementary volume).

If the authors (or the editor and other reviewers) want to include the analysis with an LTNE model, I would recommend a LTNE model presented in Wakao and Kaguei, 1982, where energy equation for a solid spherical particle is coupled with energy equation for fluid phase. In this way, the authors can simulate LTNE of a spherical particle embedded in saturated porous media.

Wakao, N. and Kaguei, S. (1982): Heat and mass transfer in packed peds. Gordon and Breach Science Publishers, Inc, 364p.

We have tested the Dispersion concentric (D-C) model by Wakao and Kaguei (1982) as suggested. However, we have not changed Fig. 8, since our findings remain unchanged. Please see the details of the model results below:

The LTNE model used in the preprint is referred to as "Continuous Solid Phase (C-S) model" in Wakao and Kaguei (1982), which includes heat conduction for the solid phase assuming the solid in a continuous phase. In Wakao and Kaguei (1982), "Dispersion concentric (D-C) model" is also suggested as an unsteady-state heat transfer model, which includes the same fluid phase heat equation as the C-S model but different solid phase heat equation considering the solid heat conduction for spherical particles. As suggested in the comment, we tested the D-C model as an alternative LTNE model using the corresponding analytical solution. The results from D-C model demonstrated greater discrepancy from the experimental data for the fluid phase temperature with the largest root mean square error (RMSE) compared to other model results (see Fig.1 below). Despite the identical effective dispersion coefficient for fluid phase was used in the LTNE model (C-S model) in preprint and the D-C model, the D-C model results showed a greater spread of breakthrough curves (BTCs) compared to the BTCs of C-S model. This comparison demonstrates that the LTNE model (C-S model) used in the preprint is suitable for our experimental data analysis, as shown in Fig. 1 below.
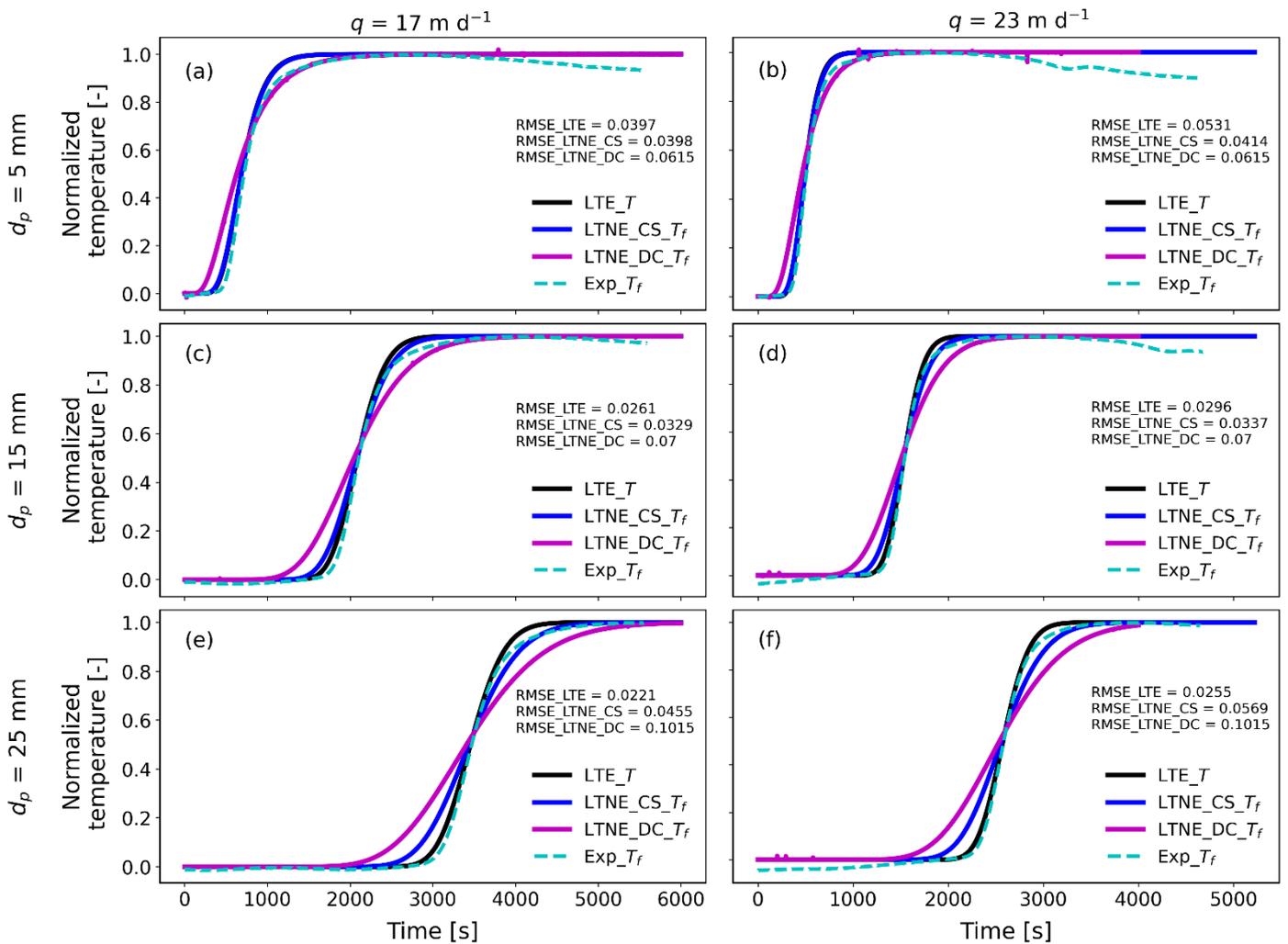

Figure 1. Thermal breakthrough curves (BTCs) from experimental data, LTE analytical model, LTNE C-S numerical model and LTNE D-C analytical model. (a), (c) and (e) demonstrate normalized temperature data from experiments and models with Darcy velocity of 17 m d^{-1} for LTNE probes with 3 grain sizes of 5 mm, 15 mm and 25 mm. (b), (d), (f) present normalized temperature data from experiments and models with Darcy velocity of 23 m d^{-1} for LTNE probes with 3 grain sizes of 5 mm, 15 mm and 25 mm. The magenta solid lines show analytical solution of LTNE D-C model, which is additionally compared to the Fig. 8 in the preprint, while blue solid lines represent LTNE (C-S) model used in the preprint. The solid black lines for LTE model and the dotted lines for experimental data are same as the original presentation in Fig. 8 in the preprint.

Calibration of temperature data

Regarding Line 225-229, it is more natural to normalize the measured temperature by the temperature difference between the initial and final temperature, as in Eq. 19, not by the final temperature. Doing a proper temperature calibration might provide temperature data, that is more compatible with the LTE model:

We agree that analysing the experimental data using normalization is appropriate. In our revised manuscript, normalized temperature values are now used for analysis, and figures with BTCs and ΔT have been updated to reflect normalized temperature differences and normalized ΔT. Consequently, all relevant results, figures and descriptions have been updated accordingly. This revision does not alter the manuscript's main message.

We have revised Fig.3-6 & Fig.8-9 (line 295, 327, 339, 349) and a relevant sentence by correcting the value and unit (line 383).

- In Figure 2, what caused the increase in the calibrated temperature at deeper depths before the arrival of the thermal front. This would not be affected by the replenishment of the water bath with tap water during the experiment. Is this affected by the laboratory air? In that case, why was the increase smaller for Figure (a), which was conducted for a longer time?

We agree that the information needs to be included and have added sentences in our revised manuscript (lines 270-273):

> "An increase of calibrated temperature before the arrival of thermal front was observed by the measurements at deeper depths for the larger grains. This may result from temperature variations during the equilibration phase to establish a uniform initial temperature. Additionally, Fig. 2 shows that the calibrated temperature at 0 second varies between sensors, likely due to limited temperature control in the laboratory, which lacks air conditioning."

Interpretation of inverse peaks

I am glad to see Figure 5, illustrating the difficulty of the experiments. In my unpublished data, I observed similar inverse peaks for smaller grains (dp = 3 mm). I attributed this to the placement of fluid temperature sensors. It is extremely hard to make sure the depth of solid and fluid temperature measurement is the same. Smaller the grains are, more difficult. When I failed to do this, I observed inverse peaks regardless of fluid flow rates. Non-uniform flow could also cause the inverse peaks, but I do not think we can eliminate the possibility of misplacement of fluid temperature sensors relative to the location of the solid temperature sensors in this experimental setup.

We agree that sensor misplacement could be a factor contributing to the inverse pulse, although we carefully positioned the fluid and solid temperature sensors on a frame. To investigate this, we analyzed experimental data by comparing $\Delta T(t)$ from a LTNE probe at different flow velocities. The results, now shown in the revised Fig. 5, replaced the previous figure in the preprint. Fig. 5 illustrates that the $\Delta T(t)$ pattern from a single LTNE probe changes with varying flow conditions, suggesting that the inverse pulse may result from altered flow pattern due to non-uniform flow. If the inverse pulses were solely due to sensor misplacement, we would expect the $\Delta T(t)$ pattern from the same LTNE probe to remain consistent. We also observed that the LTNE probe produced a similar $\Delta T(t)$ pattern with an inverse pulse across different flow conditions. Therefore, we propose that the inverse pulse could be influenced by both non-uniform flow and sensor positioning uncertainties.

Hence, we have added sentences to incorporate the updated Fig. 5 in the context (line 300-304):

"Fig. 5 shows that the normalized ΔT(t) patterns from two pairs within a LTNE replica (i.e., measurements from the same sensor positions) vary when the flow velocity changes. Additionally, the temperature differences between fluid phase measurements from two sides of a sphere demonstrate changing patterns with varying flow velocity, suggesting the different thermal front arrival in the fluid phase depending on the position near the sphere at the same depth."

Minor points

41: "at the same temperature at their interface": I believe this is true for LTNE approaches. The LTE approach assumes the temperature of the phases are the same within an REV, not just their interface.

We agree that the definition of LTE needs to be revised and have changed the sentence in line 47-48:

"This method assumes that thermal equilibrium between fluid and solid phases is reached instantaneously and is hereafter referred to as the *local thermal equilibrium* (LTE) model (deMarsily1986, Whitaker1991)"

99: Could you provide the information on the glue used (e.g., the name of the product)? Also, what is the volumetric heat capacity of the glue?

Yes, the name and the company of the product are now included in our revised manuscript. The volumetric heat capacity of the thermal conductive glue was calculated based on the given information by the company, such as mix ratio of 2 parts, specific heat capacity of each part and the cured glue.

Hence, we revised the related sentence (lines 112-113):

"Temperature sensors were carefully inserted and embedded using thermally conductive glue (Thermal Bonding System TBS20S, Electrolube, United Kingdom) with a thermal conductivity of 1.1 (W m^{-1} K^{-1}) and a volumetric heat capacity of 3.58 (MJ m^{-3} K^{-1}) to minimize heat transport influences."

100: How did you place temperature sensors next to the surface of the glass spheres? Accurately placing sensors for fluid temperatures is important to avoid the "inverse peaks".

We agree that precise sensor positioning is crucial to minimize measurement error. As shown in Figs. 1b & 1c, the temperature sensors for fluid and solid phases were secured on a PVC frame and placed at specific depths. Despite careful placement, sensor positioning uncertainties may have arisen during the packing process. This possibility is addressed in the updated Fig. 5, as previously described, highlighting the impact of non-uniform flow.

We have therefore revised the sentences in lines 270-273:

"The inverse pulse may be attributed to the non-uniform flow and/or uncertainties in sensor positioning. While we cannot rule out sensor position uncertainties, our results showed that the thermal front measured by the sensors at the same location varied with changes in flow velocity. This phenomenon of non-uniform flow was previously reported by an experimental observation when multiple temperature sensors were used at the same discrete locations along the flow path (Rau et al., 2012b)"

111: Could you describe how you achieved water saturation of the porous media? Also, did you use any thermal insulation for the column? Minimizing air in porous media and heat loss from the column is essential to get experimental data that is compatible with the LTE model.

We agree that the information needs to be included. In section 2.1, the sentence is revised including the information on insulation and ensuring water saturation.

We have therefore revised the manuscript in lines 93-95 & 141-142:

> "Our adapted experimental configuration comprises an acrylic glass column with a length of 1.5 m and an inner diameter of 0.29 m covered by a layer of thermal insulation (K-Flex 25), a refrigerated bath circulator (WCR-P22, Witeg Labortechnik GmbH, Germany), an eight-channel peristaltic pump (Ismatec Ecoline, Kinesis Australia Pty Ltd, Australia) with thermally insulated tubes by a K-Flex tube for the inflow, and an outflow tank."

> "The porous media was filled slowly with water from the bottom upwards to displace air while avoiding trapped bubbles."

131: 26-34: "C" is missing.

Correct. We have revised the sentence in our manuscript in line 150:

> "The inflow, sourced from the laboratory tap, was preheated through a heat exchanger within the refrigerated bath, maintaining a temperature between 26-34 °C"

Equation 1: "x is spatial coordinate" is missing.

We agree that the definition is missing and have added the corresponding description in our manuscript in line 176-177:

> "where T is the temperature of the bulk porous medium (°C or K), t is the time (s) and x is the distance along the flow direction (m)."

Equation 6: This analytical solution is for normalized temperature, not actual temperature T.

We agree that Equation 6 requires the calculation of normalized temperature and have revised Equation 6 and the corresponding description in line 187 & 189:

> "Here, T_{norm} is the normalized temperature (-), T_0 is the initial temperature (K) and T_1 is the temperature (K) of heat input at the top boundary (x = 0)."

183: The effective thermal conductivity of fluid includes the effect of thermal dispersion under advection. Bandai et al., 2023 was not accurate for this description. Line 206 is accurate.

We agree that the sentence needs to be corrected and have revised this as follows (line 202-203):

> "$\lambda_{f,eff}$ and $\lambda_{s,eff}$ are effective thermal conductivities of the fluid and solid phases, which describe the thermal conductivity of each phase. $\lambda_{f,eff}$ for the fluid phase includes hydrodynamic dispersion (Amiri & Vafai, 2005)"

200: 1.5 m (= L)?

Thank you for spotting the typo which is now fixed (line 224).

Figure 2: I would suggest using the same color for the temperatures measured at the same depths for both phases.

We disagree with using the same color for fluid and solid phase temperature measured at the same depth, as overlapping curves would be indistinguishable - particularly for temperatures at smaller grain sizes and the shallowest depths.

Figure 8: There is a discrepancy between the models and the data at the end of the thermal front (in addition to the end of the breakthrough curve) for q = 17.2 m d-1. What caused this discrepancy? Heat loss from the column can be one reason, but if this was the case, the discrepancy would have been larger for dp = 25 mm, which was located at a deeper depth. Or, the location of the sensors for dp = 5 mm was not far enough from the input? But, if this was the case, the discrepancy would have been larger for q = 22.8 m d-1. Another reason may be the artifact of the temperature calibration procedure.

We agree that a discrepancy exists between the model and the data at the end of the BTCs, which we attributed to non-ideal heat input from the thermostat bath. As described in section 3.1 (lines 273-276), the input temperature fluctuated due to the replenishment of the water bath with the tap water during the experiment, resulting in a decreasing tail in the BTCs at later time points.

344: "limited to 0.04 K": This is not accurate. This value is maximum normalized temperature difference in Figure 8 in Bandai et al., 2023, which can be converted to approximately 0.6 K because the temperature difference was about 15 K.

We agree that the sentence has to be corrected. Since the revised manuscript uses normalized temperature [-] instead of relative temperature rise [K], we compared the normalized temperature of Bandai et al., 2023 and our study in the revised manuscript. We have therefore revised the sentence as follows (lines 379-386):

> "In the study of Bandai et al. (2023), temperatures for fluid and solid phases were separately measured and the maximum normalized temperature difference between fluid and solid phases for 4.94 mm glass spheres with thermal conductivity of 0.76 W m^{-1} K^{-1} was up to 0.04 at a Darcy velocity of 29 m d^{-1}. In comparison, our study showed a smaller maximum normalized temperature difference of 0.02 between the two phases for 5 mm spheres with a lower Darcy velocity of 23 m d^{-1}. The smaller LTNE effects observed in our results may be attributed to the dependence of LTNE on Darcy velocities, as Bandai et al. (2023) demonstrated that LTNE effects increase with higher Darcy velocities. While a similar pattern appears in our findings, some LTNE probes displayed $\Delta T(t)$ with peaks near zero or with inverse values (Fig. 5)."

Line 379: Could you describe how you fitted the models to the experimental data to estimate the heat transfer parameters? It would be better to define a minimization problem to be solved and specify optimization algorithms used to solve it.

We agree that a quantitative evaluation of the fit should be included. RMSE values have been provided in Fig. 8 and 9 to illustrate the fitting accuracy. Optimization was conducted using the Powell method from the SciPy package within the Python programming environment.

We have revised the related sentences as follows (lines 233-235):

References

Bandai, T., Hamamoto, S., Rau, G. C., Komatsu, T., and Nishimura, T.: Effects of thermal properties of porous media on local thermal (non-)equilibrium heat transport, Journal of Groundwater Hydrology, 65, 125–139, https://doi.org/10.5917/jagh.65.125, 2023.

Gossler, M. A., Bayer, P., and Zosseder, K.: Experimental investigation of thermal retardation and local thermal nonequilibrium effects on heat transport in highly permeable, porous aquifers, Journal of Hydrology, 578, 124 097, https://doi.org/https://doi.org/10.1016/j.jhydrol.2019.124097, 2019.

Gossler, M. A., Bayer, P., Rau, G. C., Einsiedl, F., and Zosseder, K.: On the Limitations and Implications of Modeling Heat Transport in Porous Aquifers by Assuming Local Thermal Equilibrium, Water Resources Research, 56, e2020WR027 772, https://doi.org/https://doi.org/10.1029/2020WR027772, e2020WR027772 2020WR027772, 2020.

Nield, D. A. and Bejan, A.: Convection in Porous Media, Springer International Publishing, 5th edn., 2017.

Medici, G., Ling, F., and Shang, J.: Review of discrete fracture network characterization for geothermal energy extraction, Frontiers in Earth Science, 11, https://doi.org/10.3389/feart.2023.1328397, 2023.

Rau, G. C., Andersen, M. S., and Acworth, R. I.: Experimental investigation of the thermal dispersivity term and its significance in the heat transport equation for flow in sediments, Water Resources Research, 48, https://doi.org/https://doi.org/10.1029/2011WR011038, 2012a.

Rau, G. C., Andersen, M. S., and Acworth, R. I.: Experimental investigation of the thermal time-series method for surface water-groundwater interactions, Water Resources Research, 48, https://doi.org/https://doi.org/10.1029/2011WR011560, 2012b

Stallman, R. W.: Steady one-dimensional fluid flow in a semi-infinite porous medium with sinusoidal surface temperature, Journal of Geophysical Research (1896-1977), 70, 2821–2827, https://doi.org/https://doi.org/10.1029/JZ070i012p02821, 1965.

Wakao, N. and Kaguei, S.: Heat and mass transfer in packed beds, New York: Gordon and Breach Science Publishers, 1982.

Zhu, J., Hu, K., Lu, X., Huang, X., Liu, K., and Wu, X.: A review of geothermal energy resources, development, and applications in China: Current status and prospects, Energy, 93, 466–483, https://doi.org/https://doi.org/10.1016/j.energy.2015.08.098, 2015.