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FINAL PROGRAM

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16:20	Thermodynamic System Concept for Underground Temperature and Discharge Flow Assessments <i>Philippe Machetel</i>
16:50	Hydrogeochemistry and Subsurface Temperature Evaluation of Selected Hot Springs in Jiangxi Province, SE-China <i>Zhanxue Sun</i>
17:20	A Physical Basis for Exploring for High Poroperm Zones in Deep Reservoirs <i>Peter Malin</i>
17:50	Discussion
18:30	Dinner (Zhendan Restaurant/震旦园)

8:30-12:20, Saturday, June 30

SESSION 3: Geothermal Modeling

Session Chair: Philippe Machetel	
Time	Topic
08:30	Geothermal Potential of the Crust-models, Models and More Models <i>Steve Quenette</i>
09:00	Recent Development in Simulation of Enhanced Geothermal Reservoirs <i>Huilin Xing</i>
09:30	From Deep Heat Source to the Surficial Geothermal Flow: the Connection <i>Guoping Lu</i>
10:00	Formulation of a Framework for Thermal-Hydraulic-Mechanical Coupling of Geomaterials in Finite Strain <i>Ali Karrech</i>
10:30	Break
10:50	Particle Simulation of Hydraulic Fracture and Sustainable Geothermal Reservoir Fluid <i>Peter Mora</i>

question about
the dissipation due to friction
→ these heat remains
in the system

question about
the length of the system
- Stanton Number
- Reynolds Number
- Peclet Number
- Nusselt Number

$St = f(Pr, Re)$
 $Na = g(Re, Pr)$

Applicability of Open Thermodynamic System concept for underground temperature and discharge flow assessments

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Introduction

Since millenaries, modeling sciences have progressed with the unavoidable contradictions that exist between the universal properties of physical laws and the uniqueness of local observations. Models propose first theoretical concepts agreeing with certain observations but they are refuted by others. However, the resulting bouncing process is the only way to improve our knowledge about of the working of physical systems. In this paper, we propose to use Open Thermodynamic System (OTS) frameworks in order to assess temperatures and discharges of underground flows in karstic systems. The theoretical formulation is built on the first and second laws of thermodynamics. However, it also requires the existence of steady states in the Control Volume (CV) of the OTS. Such situations are necessary to cancel the heat exchanges between underground water and embedding rocks. This situation is obviously never perfectly reached in Nature where flow discharges vary with rainfalls and recessions while temperature fluctuations occur at seasonal or diurnal time scales. However, considering the low cost and the easiness of temperature record operations it could be economically and scientifically interesting to assess in which conditions temperature can be used as a conservative tracer with reasonably controlled uncertainties. In a first part we will shortly resume the results of a pumping test campaign that has been conducted on the Cent-Font (Hérault, France) fluviokarst during summer 2005. In a second part, we will develop the theoretical formalism of the OTS framework that leads to equation systems involving the temperatures and/or the discharges of the underground and surface flows involved in the fluviokarst. In a third part, this formalism will be applied to the conceptual model of fluviokarst developed by White (2003), allowing retrieving the main observed hydrologic properties of the Cent-Fonts resurgence. The fourth part will be devoted to a development of the analogy between the hydrologic functioning of fluviokarst with a chemical (in fact a mixing) reaction in a Continuously Stirred Tank Reactor, which thermodynamical properties may be consistently described with an OTS framework, the final purpose of this study being to try to assess how, and in which conditions, temperature can be used as a conservative tracer for fluviokarst.

Observations of the Cent-Fonts resurgence properties

The Cent-Font karstic system encounters the universality and the simplicity of the White's (2003) conceptual model of fluviokarst. Its hydrologic properties are well-known since 2005, thanks to the results of a thorough pumping test campaign, which purpose was to assess the spring water supply possibilities. Its watershed drains a 40-60 km² area of calcareous and dolomitic Jurassic outcrops that joins its base level at the Hérault River. As a typical fluviokarst, it consists of a plateau incised by a stream (Buèges Stream) displaying first a surface course, then an underground course starting with a swallow zone. This underground network is a part of the Cent-Fonts resurgence Conduit System (CS) (Dubois, 1962, Schoen et al, 1999) that also drains a basic matrix-conduit flow (Q_M) percolating through an epikarstic layer (Pételet-Giraud et al., 2000). The detailed structure of the CS near the resurgence displays an outlet cave, roughly « Y » shaped, with two sub-horizontal branches that join above a deep blind chimney (Fig. 1). The resurgence flows into a neighbor river (Hérault River) through a shallow network of springs that gush out a few tens of centimeters above the base level but also directly through

the bottom of the Hérault riverbed (Schoen et al., 1999).

During the 2005 Cent-Fonts resurgence campaign, temperatures, discharges and hydraulic heads have been recorded in boreholes. Complementary hydraulic properties have been obtained from the a step-drawdown test, from timed volumetric gauging and geochemical samplings (*Ladouche et al. 2002*).

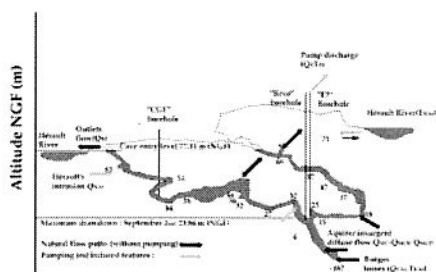


Fig. 1 Unrolled 3-D speleological map of the Cent-Fonts conduit system near the resurgence. Vertical distances are given in m.

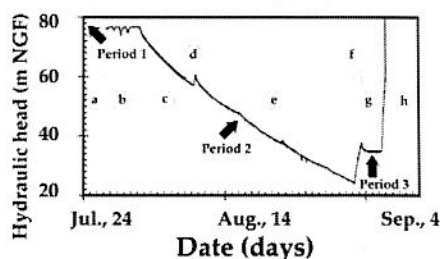


Fig. 2: Evolution of the hydraulic head recorded in the Conduit system during the pumping tests. a) pre-pumping, b) step drawdown test; c) constant pumping; d) recovering test; e) constant pumping phase; f) recovering, g) equilibrium-pumping.

Under natural conditions (without pumping), the basic matrix-conduit flow (Q_M) gathers in the CS with the intrusive flow of the upper stream (Q_U) to feed a resurgence output flow (Q_O), which has been assessed between 0.300 and 0.400 m³/s by the results of the step pumping test (end of Period 1 on Fig. 2). During the period 2 of the pumping tests (Fig. 2), the deep drawdown conditions allowed measuring a lower bound value of 45 l/s for Q_N (the drawdown induced intrusion from neighbor base level river Hérault) by in-situ timed volumetric gauging. Furthermore, analyses of water samples collected in the CS, in the Buèges Stream, in the Hérault River, and at the output of the pumping device allowed revising Q_N ranges from 0.039 to 0.048 m³/s (for Ba), from 0.060 to 0.083 m³/s (for Sr) and from 0.077 to 0.087 m³/s (for Rb) with an averaged value of $Q_N = 0.066$ m³/s. Finally, the rapid drop of the pumping rate a few hours after the starting of the equilibrium-pumping has also argued in favor of a very short transient effect and low value for the extra contribution of the matrix flow induced by drawdown (Q_{Md}).

Open Thermodynamic System formalism

As it has been mentioned in the introduction, these tests were also including temperatures and discharges recording in holes, stream and river. It is tempting, looking at the easiness and low cost of temperature recording to try to use them assessing the hydrologic properties. However, temperature cannot be directly considered as a conservative tracer. In this section we describe a theoretical framework for which, under certain assumptions, we find that temperature can be considered to assess at least the first order of the hydrologic properties. This framework is based on OTS formalism characterized by energy and water permeable boundaries delimiting the CV. The control volume used in our analysis is the saturated part of the karstic Conduit System, over which we will check the mass and energy balances (Fig. 3).

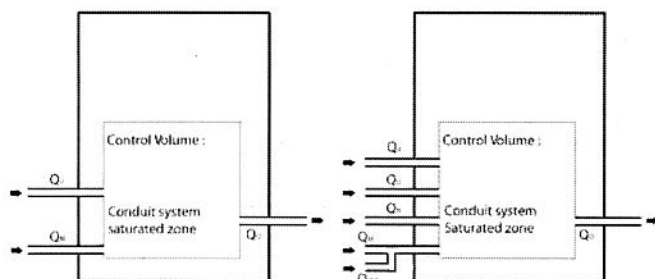


Fig.3 An Open Thermodynamic System OTS is characterized by matter and/or energy permeable boundaries, which delimit the control volume (CV) over which mass and energy balances will be considered. Left part: application to White's fluviokarst model during the recession context (input flows are Q_M and Q_U). Right part: pumping test context. During the pumping, the emptying of the cave will be taken into account as a recharge contribution to the saturated part of the CS (Q_W). The drawdown triggers the intrusion from the neighbor stream (Q_N) and a supplementary matrix-conduit flow (Q_{NM}) that adds to the basic one (Q_M). The pump output remains the only discharge of the CV.

The situation is slightly more complex during pumping test experiments since two more contributions add to the mixing process occurring in the CV, which remains defined as a saturated part of the conduit system (Fig. 2-right panel). The emptying of the conduit system acts as a supplementary contribution (Q_{CS}). Furthermore, the hydraulic head induced by drawdown between the base level and the actual water table in the CS triggers a vadose intrusion of the neighbor river (Q_N) and an additional component appears for the matrix-conduit flow (Q_{Md}). The hydraulic head also induces the drying of the spring and the pumping device becomes the only output flow. Thus, we can consider that the natural configuration (Fig. 2 - left part) is a particular case of the pumping test configuration by considering that $Q_{Md} = Q_d = Q_N = 0$.

One of the major advantages of the OTS formalism is that it does not require accurate knowledge of the CV boundaries because it is possible to replace the integration of water fluxes through the walls of the CV by integrations over the CV. A continuity equation appears then that links the discharges of the various flows (Eq.1).

$$\sum_{output} Q_o = \sum_{input} Q_i \quad (1)$$

Furthermore, while matter and energy can cross the OTS boundaries, the first law of thermodynamics stipulates that the internal energy variations in the CV are equal to the sum of the energy differences between the incoming and the outgoing flows, taking into account the work done by the system. Following Vidal (1997), the total internal energy variation (dE) can be calculated as the sum (on the various flow - index i) of the enthalpy by unit of mass (h_i), of the potential energy ($e_{pot,i}$), of the kinetic energy ($e_{cin,i}$), of the external heat transfer ($d\Phi_j$) and of the works exchanges with the surrounding (dW_k) (Eq. 2).

$$dE = \sum_i (h_i + e_{pot,i} + e_{cin,i}) dm_i + \sum_j \delta\Phi_j + \sum_k \delta W_k \quad (2)$$

Now, if steady conditions are achieved in the CV, the internal energy variations dE cancel. This is also the case for the variations of potential energy and kinetic energy. Then, the first principle of thermodynamic can be summed up in a balance between the enthalpy and the heat and work received by the CV. If we consider now that the flow transfers occur without heat and work exchanges, it is possible to compensate (Eq. 3) the sum of the enthalpies of the flows entering the CV (H_{input}) with those of the flows escaping the CV (H_{output}) (e.g. Van Wylen and Sonntag, 1985).

$$H_{input} = \sum_{input} h_i \rho_i Q_i \Delta t ; H_{output} = \sum_{output} h_i \rho_i Q_i \Delta t \quad (3)$$

As it is convenient for water within karstic CS we will consider that enthalpy variations measure the temperature variations without chemical contribution. Then their expression depends only on the thermal capacity and on the temperature (with an arbitrary reference temperature T_a).

$$h_i = Cp_i (T - T_a) \quad (4)$$

Finally, we will assume that density and thermal capacity C_p can be considered as constant, to retrieve the classical mixing equation for conservative tracers (Eq. 5) but now linking temperature and heat transfers between various flows.

$$\sum_{input} Q_i T_i = \sum_{output} Q_o T_o \quad (5)$$

Eq. 1 and Eq. 5 form the basis of a linear system that can be solved to calculate two unknown discharges or temperatures in the CV of the OTS. However, this result relies on the existence of a thermal steady state in the CV. Such conditions are obviously never strictly reached in Nature even if they are approached, for discharges, during "short" time intervals of the natural recession. They are also approached during particular phases of the pumping tests (as constant pumping or equilibrium pumping). However, diurnal and seasonal temperature fluctuations exist. The firsts can be damped with a 24-hours moving averaging (Mosheni and Stephan, 1999; Bogan et al., 2003; Bogan et al., 2004) but meteorological or seasonal trends that evolve over a few days or weeks may jeopardize the steadiness within the OTS. Conscious of this, we have decided to explore the possibilities opened by the OTS framework on the "steadiest" periods available in the pumping test data. In order to benefit of the flattest

part of the recession curve, we have restrained the used data range to the period of summer during which no heavy rainfall occurred on the watershed. And, in order to reach the steadiest conditions for the hydraulic regimes of the flows, the method has been focused on the pre-pumping period, on the equilibrium pumping and on the long term pumping (Fig. 2).

Retrieving the Cent-Fonts hydrologic results from the OTS model

Pre-pumping period (Period 1 - Fig. 2):

Under natural conditions, the water table exceeds by a few tens of centimeters the base level of the karstic system (given by the neighbor river). This weak hydraulic head is sufficient to prevent the intrusion from the neighbor river in the CV. Then Q_O , gathers Q_M and Q_U . In order to test the possibilities of using temperature as a conservative tracer within the OTS framework, we calculated the two unknown flows Q_M and Q_O using the system of Eq. 1 and Eq. 5 rewritten as Eq. 6.

$$Q_M = \frac{Q_U(T_O - T_U)}{(T_M - T_O)} \quad (6)$$

$$Q_O = Q_M + Q_U$$

T_U temperature records display night and days oscillations of 0.2 to 0.4 °C. Q_U also displays a 24-hours periodic behavior due to the water catchments of the villages upstream of the swallow zone (Fig. 4 - left). These oscillations have been damped by calculating a 24-hours moving averaging before using the data. In order to get a recession slope as flat as possible, we have also limited the application of the method to the latest date as possible, over a six days period just before the starting of the pumping experiments.

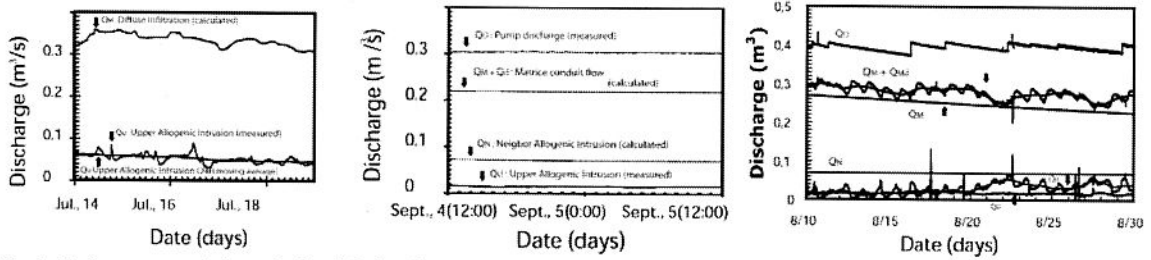


Fig. 4: Discharges recorded or calculated during the pre-pumping period (left), the equilibrium pumping (center) and the constant pumping (right). The diurnal periodic behaviors are damped thanks to 24-hours moving averaging, thus less regular behavior due to water catchments upstream of the swallow zone.

The results displayed in fig. 4 (left part) give $Q_M = 0.336 \text{ m}^3/\text{s}$ July 16th (12:00). The extrapolation of this result with the recession coefficient of the Cent-Fonts resurgence calculated by Ladouche et al. (2002) from three years of observations leads to $Q_M = 0.305 \text{ m}^3/\text{s}$ and $Q_O = 0.347 \text{ m}^3/\text{s}$ at the dates of the step pumping (Fig.2). This result is consistent with the drying of the source obtained with the pumping step of $0.402 \text{ m}^3/\text{s}$ (July 30th) and the non-drying observed for the $0.301 \text{ m}^3/\text{s}$ pumping step (July 28th).

Equilibrium-pumping (period 3-Fig.2)

The equilibrium-pumping (Fig.2 - period 3) was following one month of constant pumping at $0.400 \text{ m}^3/\text{s}$. The stabilization of the drawdown ($35.0 \pm 0.1 \text{ m}$) was obtained after a few hours for $Q_O = 0.304\text{-}0.305 \text{ m}^3/\text{s}$. This drawdown was induced the vadose intrusion of the neighbor river. Thus, Q_U and Q_N , contributed with the matrix-conduit flows Q_M and Q_{Md} to equilibrate the discharge of the pump Q_O . The OTS formalism has been used during this equilibrium pumping to calculate from Eq. 1 and Eq. 5 the two unknown discharges Q_N , and Q_M .

$$Q_N = \frac{Q_O(T_O - T_M) - Q_U(T_U - T_M)}{(T_N - T_M)} \quad (7)$$

$$Q_M = \frac{Q_O(T_N - T_O) - Q_U(T_N - T_U)}{(T_N - T_M)}$$

In order to approach physical conditions as close as steadiness in the CV, we have restrained the

calculations over a 24-hours data range from September 4th (12:00) to September 5th (12:00) (Fig. 4 center), while the hydraulic head was stabilized in the conduit system (Fig. 2). At that time, Q_U remained quite constant and the solving of Eq. 7 gave almost constant results with $Q_N = 0.070 \text{ m}^3/\text{s}$ and $Q_M + Q_{Md} = 0.219 \text{ m}^3/\text{s}$. This latter is only a few l/s higher than Q_M that suggests a very low Q_{Md} , consistent with the very rapid decrease of the transient contribution at the beginning of the equilibrium pumping.

Constant pumping (period 2 – Fig. 2)

With the application of the method on Periods 1 and 3 we have been able to calculate the basic matrix-conduit flow recharging the conduit system and the intrusion of the neighbor river. These first results bring two “corner stones”, separated by the constant pumping, and between which it is possible to calculate Q_M and Q_{Md} . The constant pumping may seem the farthest from generating steady physical conditions in the CV since during Periods 1 and 3, its volume was constant. However, the lowering of the water table in the CS was consecutive of a constant pumping rate that induced a monotonically deepening of the drawdown proportionally to time (Fig. 2) (Except for short recovering periods that have been excluded of our computations). Furthermore, the neighbor river intrusion acted like a vadose flow, inducing an almost steady configuration in spite of the increasing drawdown conditions (*Ladouche et al., 2005*). Considering the almost constancy of the discharges of the input and output flows, Eq. 1 and Eq. 5 have been rewritten as Eq. 8 and applied for the calculations of Q_M and Q_d .

$$\begin{aligned} Q_M &= \frac{Q_O(T_O - T_d) - Q_U(T_U - T_d) - Q_N(T_N - T_d)}{(T_M - T_{CS})} \\ Q_d &= \frac{Q_O(T_M - T_O) - Q_U(T_M - T_U) - Q_N(T_M - T_N)}{(T_M - T_d)} \end{aligned} \quad (8)$$

The results of calculations for Q_M and Q_{Md} are presented on the right part of Fig. 4. Q_M results induce an almost constant contribution of Q_{Md} . Indeed, in spite of the increase of the hydraulic head due to drawdown increase, the contribution of Q_d to the CV remains comprised between 0.030 and 0.050 m^3/s without clear increasing trend. This betrays the effect of a short transient regime, going with the hydraulic head increase, and consistent with the few hours observed at the beginning of the equilibrium-pumping phase.

Finally, the numerical analyses conducted on the three “steadyest” periods of the pumping tests lead to retrieve consistently the observed hydrological behavior of the karstic system. But, if this self-consistence is encouraging, the utilization of temperature as a conservative tracer in the OTS framework requires more attention to be validated. It is necessary to try to separate what could be a coincidental local agreement with what could be the consequence of a more general property of the fluviokarst functioning. This is this aspect which is developed in the last part.

Analogy of Mixing in the CS of Fluviokarst with CSTR

In summary, the first order of the field hydrologic properties observed at the Cent-Fonts resurgence are retrieved by the calculations based on the OTS framework when the temperature is considered as a conservative tracer. If this agreement is a necessary condition to develop this method, it is not sufficient to fully validate it. At this stage, it is difficult to decipher between what could be a coincidental local agreement with what could represent a consistent description of fluviokarst properties. However, the mixing process flows in the open conduit system of a fluviokarst is analogous to a chemical reaction in a Continuous Stirred Tank Reactor (CSTR). Indeed, the flows are continuously introduced in the conduit system while the effluent water is recovered at the output. Similarly, mixing of flows within the CS of fluviokarst works like a chemical reactor, since the enthalpy of the various water flows is conserved within the CV except for the part that exchanges with the embedding rocks. This last contribution is analogous to the cooling that is necessary to evacuate the heat produced by exothermic reaction in continuous reactor or to the heat that has to be brought to maintain an endothermic reaction.

In the water saturated part of a fluviokarst CS, the Q_U and q_B flows swept the heat by convective-advective processes (Fig. 8) while conductive heat flux due to the temporal fluctuations may flow through the CV walls either to reheat or cool locally the rock matrix. This is particularly true for diurnal fluctuations which are

damped during the underground transfer along the CS. The case of the seasonal temperature fluctuations is

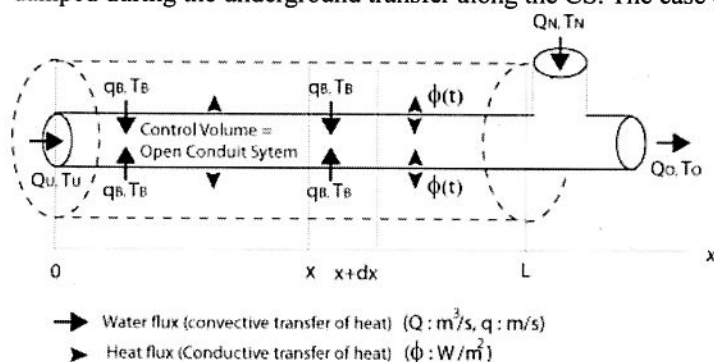


Fig. 5: The mixing process in the fluviokarst Conduit System is analogous to a chemical reaction in a Continuous Stirred Tank Reactor (CSTR).

less simple and will depend on the relative time scales between the underground travel from the beginning to the end of the CS and the one of the seasonal fluctuation. The model presented here will parameterized this phenomenon with the illustration of the case of the Cent-Font resurgence whose underground travel time is known from water tracing (Dubois, 1962, Schoen et al, 1999).

Conclusion

Under certain conditions, the combination of thermometric and mass equations, combined with continuous recording of temperatures in stream and boreholes may allow accurate assessments of the various flows in fluviokarst. This method assumes that temperature can be considered (under sufficient conditions) as a conservative tracer. This property is due to the nature of the mixing process in the fluviokarst CS that is analogous to a chemical reaction in a Continuous Stirred Tank Reactor (CSTR). Indeed, the part of heat that is exchanged with the embedding rocks is limited by the convergence of flows toward the CV. This mechanism cancels the heat exchanges for the diurnal fluctuations and also reduces those that are due to seasonal variations of temperature. Such properties if they are confirmed by our next studies may bring new tools for underground fluid temperatures and discharges that may also offer potential applications for geothermal studies

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