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Geoscientific Model Development Discussions

Interactive comment on "*HydrothermalFoam* v1.0: a 3-D hydro-thermo-transport model for natural submarine hydrothermal systems" *by* Zhikui Guo et al.

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1 Physical meaning of terms in the equation of change of internal energy

As the discussion of the paper is still open, we would like to take the chance to elaborate a bit more on the importance and meaning of the different terms in the equation of change of internal energy. We had posted previously how that equation can be written with temperature as primary variable. We hope that the underlying thermodynamic identifies and mathematical transformations are sufficiently clear now and that the presented benchmarks in the main text convincingly demonstrate their correctness.

The resulting "temperature" equation contains two terms that are often neglected and the reviewers encouraged us to elaborate more on those terms. We did so in the revised version of the manuscript but did not provide an in-depth discussion. The reason being that we would like to have the main text focused on making a state-of-the-art and well-documented 3-D hydrothermal flow model available to the wider submarine hydrothermal community. That is what this paper is about.

That said, we also feel that GMD's "author comments" provide the space to have these extra discussions. So let's discuss those terms! This is the equation of change of internal energy written in terms of temperature as primary variable. It's detailed derivation can be found in the accompanying author comment #2. The terms in question are marked in purple.

$$\begin{aligned}&(\varepsilon\rho_f C_{pf} + (1-\varepsilon)\rho_r C_{pr})\frac{\partial T}{\partial t} = \nabla\cdot(k_r\nabla T) - \rho_f C_{pf}\vec{U}\cdot\nabla T \\ &+\frac{\mu_f}{k}\parallel\vec{U}\parallel^2 - \left(\frac{\partial ln\rho_f}{\partial lnT}\right)_p\left(\varepsilon\frac{\partial p}{\partial t} + \vec{U}\cdot\nabla p\right)\end{aligned} \tag{1}$$

The first term describes viscous dissipation, so has a clear physical meaning. A discussion of it can be found in Garg and Pritchett (1977). The second term contains two components: a component of pressure volume work that is expressed as the substantial derivative of pressure, when reformulating the equation of change of internal energy in terms of enthalpy (compare equations 1 & 8 in Author Comment #2) and, more importantly, the pressure dependence of enthalpy (Fig. 1). Remember that we switch from enthalpy to temperature as primary variable by using the thermodynamic identity:

$$dh_f = \frac{\partial h_f}{\partial T}_p dT + \left(\frac{\partial h_f}{\partial p}\right)_T dp = c_p dT + \left[V - T\left(\frac{\partial V}{\partial T}\right)_p\right] dp \tag{2}$$

While the specific heat, c_p, describes how specific enthalpy changes with temperature, the term in square brackets describes how it changes with pressure. Fig. 5 shows $\left(\frac{\partial h_f}{\partial T}\right)_p$ and $\left(\frac{\partial h_f}{\partial p}\right)_T$ as functions of p and T for pure water. In the incompressible regime, enthalpy is mainly a function of temperature; under near critical, and vapor/vapor-like conditions when the fluid becomes increasingly compressible, the pressure-dependence of enthalpy starts to matter.

The physical meaning of these terms in equation 1 becomes clear when we consider the identity $\frac{\partial ln\rho_f}{\partial lnT} = \frac{T}{\rho_f}\frac{\partial \rho_f}{\partial T} = -T\alpha_f$, where $\alpha_f \equiv -\frac{1}{\rho_f}\frac{\partial \rho_f}{\partial T}$. With this, we can write the energy equation as:

$$\begin{aligned}(\varepsilon\rho_f C_{pf} + (1-\varepsilon)\rho_r C_{pr})\frac{\partial T}{\partial t} = \nabla\cdot(k_r\nabla T) - \rho_f C_{pf}\vec{U}\cdot\nabla T \\ +\tfrac{\mu_f}{k}\parallel\vec{U}\parallel^2 + T\alpha_f\left(\varepsilon\tfrac{\partial p}{\partial t} + \vec{U}\cdot\nabla p\right)\end{aligned} \tag{3}$$

The last term now takes a more familiar form, it describes adiabatic effects.

To visualize this, we go back to the three 1-D benchmark tests presented in the main text but now we also present the results, when the "purple" terms in the energy equation are neglected (dashed purple lines). The first test is in the liquid single-phase regime, the fluid is largely incompressible, and the terms in question do not matter (Fig. 2). All solutions match the reference solution obtained with HYDROTHERM (Fig. 2). The situation is different for the second, near critical, and third, pure vapor, test (Fig. 3 and 4). Here the pressure dependence of enthalpy does matter and the reference solution can only be matched when it is accounted for. Remember that HYDROTHERM neglects viscous dissipation but solves the equation of change of internal energy in conservative divergence form with specific enthalpy as primary variable (Faust and

Mercer, 1979):

$$\frac{\partial(\varepsilon\rho_f h_f + (1-\varepsilon)\rho_r h_r))}{\partial t} = \nabla\cdot(k_r\nabla T) - \nabla\cdot(\rho_f h_f\vec{U}) - \frac{\partial \varepsilon p}{\partial t} + \vec{U}\cdot\nabla p \tag{4}$$

The final question is if those terms matter for submarine hydrothermal systems. Here the answer obviously depends on the setup and especially the vertical extent of the circulation zone - but in general the answer is "yes". High temperature hydrothermal systems have been shown to operate close to maximum efficiency (Jupp and Schulz, 2000, 2004). A consequence is that the upwelling temperature is typically the one that maximizes heat transport by buoyant flow (Driesner 2010). Jupp and Schulz, (2000) developed the concept of "fluxibility", a property that describes how efficient buoyant heat transport is. Hydrothermal plumes tend to detach from a thermal boundary layer, where F is large. Fig. 6 shows that the region where F is large corresponds to those p, T conditions, where adiabatic effects matter. That is the reason why submarine hydrothermal flow models should account for that term. We hope that readers will find these extra thoughts and considerations helpful, but, for the reasons given above, we have not included them into the main text.

Fig. 1. Enthalpy as a function of pressure and temperature. Dashed lines are contours of enthalpy. The other annotations are the same as what in figure 1 in the manuscript.

Fig. 2. Flow along a pressure gradient in the single-phase liquid regime (Model 1). Enthalpy is only weakly dependent on pressure and all solutions match the reference HYDROTHERM solution. The purple lines are for a model that does not account for the "purple" adiabatic and dissipation terms in equation 1&3.

Fig. 3. Flow along a pressure gradient at near-critical conditions (Model 2). The temperature drop within the from the left invading hot fluid is related to adiabatic effects. Note in Fig. 1 (white line) how enthalpy is constant and temperature drops along this limb of the flowpath. The purple lines are for a model that does not account for the "purple" adiabatic and dissipation terms in equation 1&3.

Fig. 4. Flow along a pressure gradient at pure vapor conditions (Model 3). Again the pressure dependence of enthalpy matters and the reference solution is only matched, when the respective (purple) terms are present in the energy equation. The purple lines are for a model that does not account for the "purple" adiabatic and dissipation terms in equation 1&3.

Fig. 5. Enthalpy change with pressure and temperature. dH/dp and dH/dT as a function of pressure and temperature are shown in (a) and (b), respectively. The other annotations are the same as what in Fig. 1. Note that panel (a) shows absolute values.

Fig. 6. Adiabatic temperature gradient (a) and normalized fluxibility (b).

References

Garg, S. K., & Pritchett, J. W. (1977). On pressure-work, viscous dissipation and the energy balance relation for geothermal reservoirs. Advances in Water Resources, 1(1), 41–47. https://doi.org/10.1016/0309-1708(77)90007-0

Jupp, T., & Schultz, A. (2000). A thermodynamic explanation for black smoker temperatures. Nature, 403(6772), 880–883. https://doi.org/10.1038/35002552

Jupp, T. E., & Schultz, A. (2004). Physical balances in subseafloor hydrothermal convection cells. Journal of Geophysical Research: Solid Earth, 109(B5). https://doi.org/10.1029/2003JB002697

Driesner, T. (2010). The interplay of permeability and fluid properties as a first order control of heat transport, venting temperatures and venting salinities at mid-ocean ridge hydrothermal systems. Geofluids, 10(1-2), 132–141. https://doi.org/10.1111/j.1468-8123.2009.00273.x

Faust, C. R., & Mercer, J. W. (1979). Geothermal reservoir simulation: 1. Mathematical models for liquid- and vapor-dominated hydrothermal systems. Water Resources Research, 15(1), 23–30. https://doi.org/10.1029/WR015i001p00023

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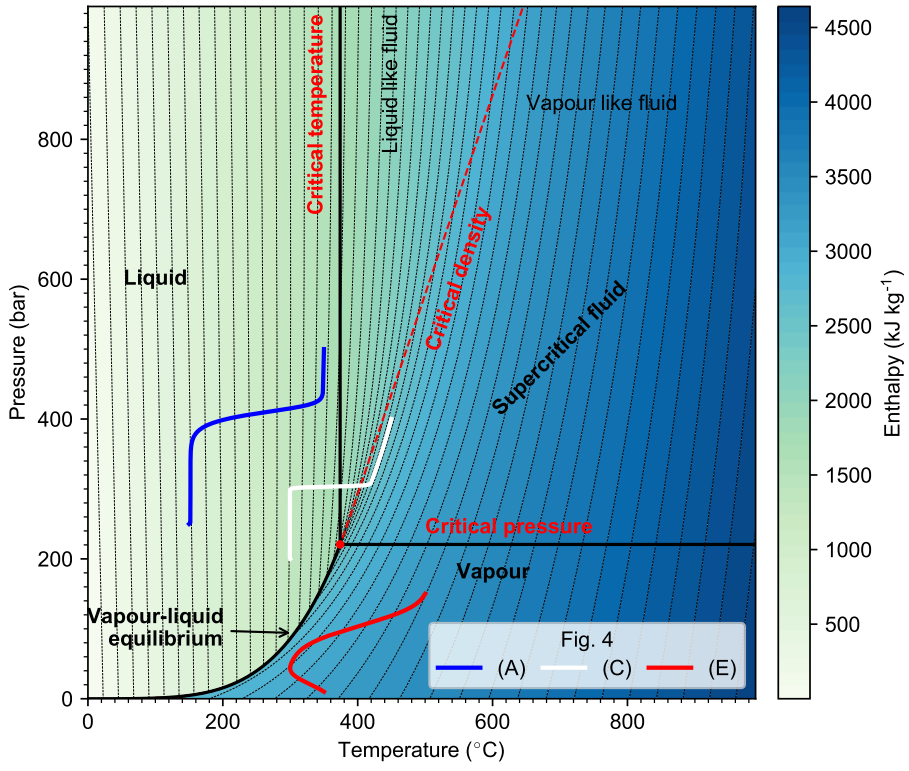

Fig. 1.

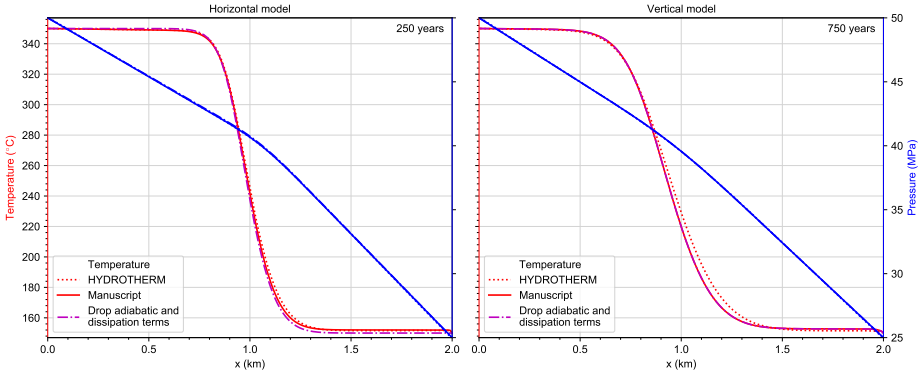
Horizontal model
250 years
Vertical model
750 years
Temperature (°C)
Pressure (MPa)
x (km)
Temperature
HYDROTHERM
Manuscript
Drop adiabatic and dissipation terms

Fig. 2.

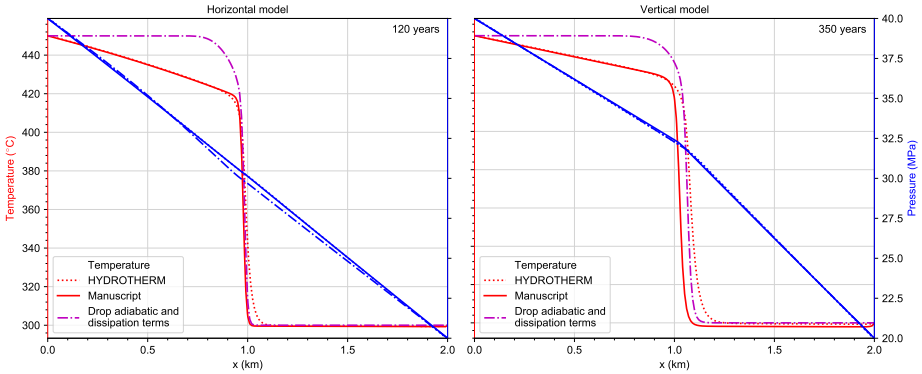
Horizontal model
120 years
Vertical model
350 years
Temperature (°C)
Pressure (MPa)
x (km)
Temperature
HYDROTHERM
Manuscript
Drop adiabatic and dissipation terms

Fig. 3.

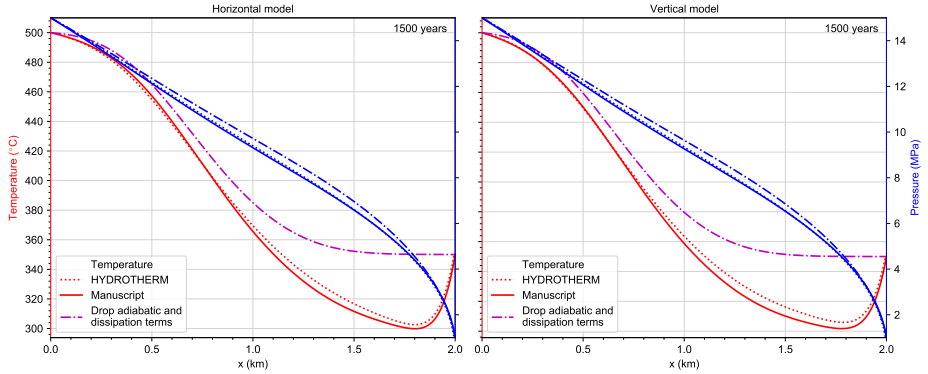
Horizontal model
Vertical model
1500 years
Temperature (°C)
Pressure (MPa)
x (km)
Temperature
HYDROTHERM
Manuscript
Drop adiabatic and dissipation terms

Fig. 4.

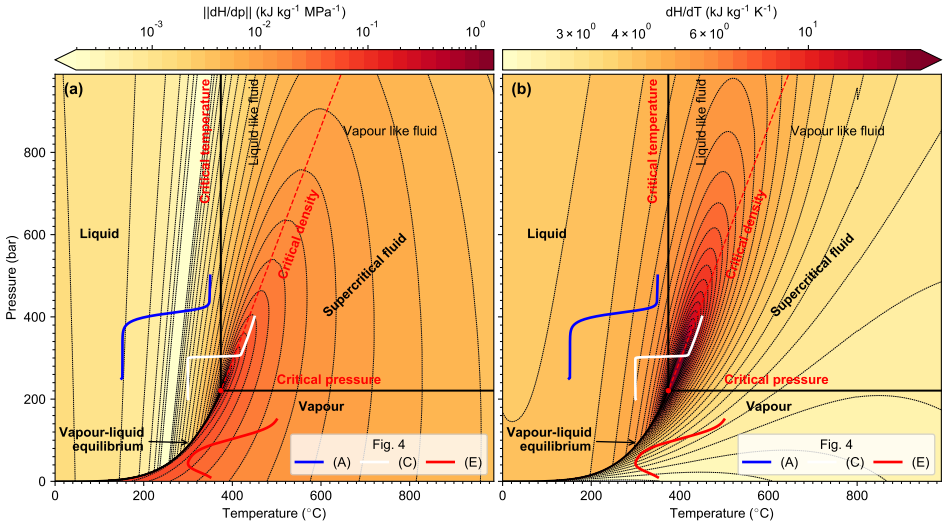
||dH/dp|| (kJ kg-1 MPa-1)
dH/dT (kJ kg-1 K-1)
(a)
(b)
Liquid
Vapour like fluid
Liquid-like fluid
Critical temperature
Critical density
Supercritical fluid
Critical pressure
Vapour
Vapour-liquid equilibrium
Fig. 4
(A)
(C)
(E)
Pressure (bar)
Temperature (°C)

Fig. 5.

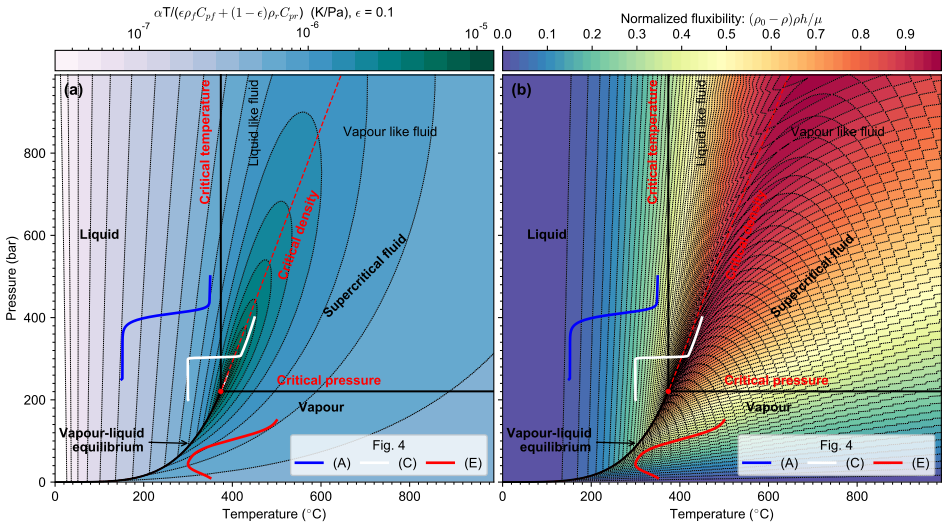
$\alpha T/(\epsilon\rho_f C_{pf} + (1-\epsilon)\rho_r C_{pr})$ (K/Pa), ϵ = 0.1
10^{-7}
10^{-6}
10^{-5}
Normalized fluxibility: $(\rho_0 - \rho)\rho h/\mu$
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
(a)
(b)
Critical temperature
Liquid like fluid
Vapour like fluid
Critical density
Supercritical fluid
Liquid
Critical pressure
Vapour
Vapour-liquid equilibrium
Fig. 4
(A)
(C)
(E)
Pressure (bar)
0
200
400
600
800
Temperature (°C)

Fig. 6.