1 Introduction

Hydrothermal systems arrive when water interacts with volcanic gases at depth, boiling off the water to create steam which, along with the gases, rises to the surface. As it moves towards the surface the steam expands and so the mixture arrives at the surface with considerable speed, typically several 10s of m/s, where it exits through a fumarole and forms a gaseous plume which may then be advected by the wind. Due to the high heat capacity of water, considerable amounts of heat, as well as mass, can be transported in this way and thus this mechanism represents a major part of the heat budget at many hydrothermal sites. For monitoring purposes it is thus important to quantify these fluxes and track them over time. However in situ measurement devices such as pitot tubes or anemometers are prone to chemical attack and or clogging due to the generally acidic conditions (fumerolic gases often contain significant quantities of HCl and other corrosive species CITE). Additionally, the volumetric flux is of interest to geochemists as this can be multiplied by chemical abundance to obtain the chemical species flux. It is thus interesting to attempt to quantify these fluxes using remote sensing techniques, notably visible or thermal cameras, though of course it is not a simple task to obtain speeds from still images of even video. Recently, techniques such as optical flow (Tournigand) and pseudo PIV (Gaudin) have been applied to thermal and visible video yet even these analyses cannot by themselves yield the full range of source conditions that are required to sufficiently quantify the heat and mass flux at the vent, in particular as measuring plume velocity near the vent suffers from resolution problems (there are few velocity vectors calculated where the plume is narrow). Instead, in this work we propose to apply a wind affected plume model (Aubry et al, 2017) to data taken from natural and laboratory plumes and, through an inverse modelling process, obtain the required source conditions. Our approach can be directly applied to gaseous plumes but can also be extended to particle laden plumes.

2 Modelling

Steady 1D models of a plume rising through a quiescent ambient are written as a set of coupled conservation equations for mass, momentum and either energy (enthalpy) or buoyancy (i.e. gravitational potential energy) LOTS OF CITES. To close the equations, an additional assumption must be made to relate the inflow rate of ambient fluid through entrainment to the axial (”upward”) motion of the plume. For 1D models, this is generally done through a single entrainment coefficient, $\alpha_e = u_e/\bar{u}$. Classically, the entrainment coefficient is taken to be a constant (MTT56, Woods88) whose value varies from about 0.1 to 0.15 according to whether the plume motion is dominated by momentum of buoyancy (assuming that velocity and buoyancy profiles can be represented by ”top hat” functions, Sparks97) though later work has shown that α_e depends locally on the developing velocity, buoyancy and shear profiles (Kaminski et al, 2005; Carazzo et al, 20??).

When wind is present, it causes the plume to bend to a greater or lesser degree according to its strength relative to the upward plume velocity. The inclined plume continues to incline and wind entrainment contributes to the axial momentum of the plume. For modelling purposes, the conservation of momentum thus has components parallel and perpendicular to the plume motion. The contribution of wind to the mass flux can be accounted for through an additional entrainment coefficient which this time relates ... and typically has a value of around 0.9

(Carazzo et al, 2016; Aubry et al, 2017). Wind was modelled as either a constant at all heights of monotonically increasing according to ... ABL MODEL ?

For particle-free plumes where density differences between plume and the environmental fluid are slight it is justified to apply the Boussinesq approximation. Under this condition the conservation equations reduce to ... DO B EQNS ALLOW FOR TEMP EFFECT ON DENSITY? (Aubry et al, 2017). Otherwise???

The solution of this model provides a prediction of the spatial extent of the plume (width as a function of axial distance), plume velocity and density (dilution relative to the source concentration).

TEMP OR CONC. T NOT PASSIVE TRACER Particularly from the latter, we can then deduce a temperature field for the plume. Additionally we note that the natural plumes are not completely opaque and thus calculate a brightness temperature based on an emmissivity of ??? thus producing a synthetic plume image as per Cerminara et al, 2014.

2.1 RADIATIVE MODEL - necessary?

In order to compare between the model and our data, we use the temperature field coupled to a radiative law...

3 Inverse model

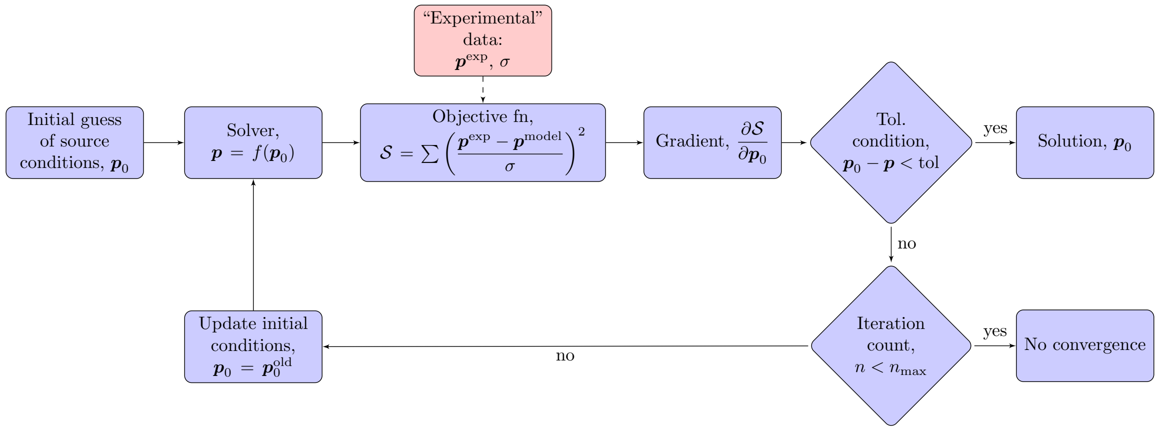
To initiate the inversion process, a guess at the source conditions needed to be made. As the set of equations to be solved are non linear, the cost function is also non linear and, more importantly, not convex, meaning that there is not a well-defined global minimum. Thus a poor choice of initial conditions may lead to the model converging to a local but not global minimum. CALC VEL FROM PIV, WIDTH AND ANGLE FROM IMAGE ANALYSIS, TEMP -¿ DENSITY,

inversion of the model with the dataset consisted in the calculation of a cost function, $\mathcal{S}$, and the gradient of this function with respect to a set of source parameters, $\boldsymbol{p}$, and then using the gradient to iteratively update $\boldsymbol{p}$ until a "best fit" is achieved, which occurs when $\mathcal{S}$ is minimised.

Following Cerminara et al (2014) we take $\mathcal{S}$ to be the sum of squared differences between the experimental and synthetic data. Specifically, we compare the mean temperature/concentration, plume width, mean plume speed and mean buoyancy along the midline of the plume at a given location, s. These variables depend essentially on the values of the source parameters, $\boldsymbol{p} = (q_0, m_0, f_0, \theta_0)$ so the best estimation of $\boldsymbol{p}$ occurs when the cost function is minimised. Iteration of the normal equations thus yields this solution.

4 Datasets

- My stuff from la S
- GCs bent over plume data
- Another good expt in windless conds
- Steam stack at les Czeaux from 2016-11



- James/Stuart from Washington

In all cases:

- preprocessing to remove background (Max's algorithm?)

- edge detection

- inverse modelling (c.f. Matteo's paper)

- intensity = f(conc. tracer or temperature)

    - $c = (Q_0/Q)c_0$
    - $T = (Q_0/Q)T_0$???

5 (Thermal) image processing

We used a Janoptiks ThermaCam HD thermal camera which is sensitive to infrared radiation in the 8-14 micron (thermal infra red - TIR) waveband to record the plumes at La Soufrire. The camera sensor consisted of a 640x480 pixel array of bolometers and the recordings were made using either a 15 or 30 mm fixed focal length lens such resulted in HFOV of ?? Or ??, respectively. The images were taken at a distance, d, of a few metres (d was precisely recorded using an on-board laser distance ranger).

Simultaneously to the image recording, we took measurements of the wind speed and direction, atmospheric pressure and temperature, relative humidity (RH) using a Kestrel 5500 portable weather station. These values were later fed into a line-by-line atmospheric radiance model (Py4CAtS/GARLIC, CITE) which allowed us to calculate the optical depth of the atmosphere, D, from which we calculate transmissivity as

$$\tau = e^{-D}$$

(CITES).

The experimental dataset

VALIDATION OF RESULTS

- Verify temp from independent measurements at vent.
- pitot tube measurements for vel. + density
- constraints placed on initial conditions (provided by independent measurements) should automatically validate the results.

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