Deep-Sea Research I 92 (2014) 41–55

Contents lists available at ScienceDirect

Deep-Sea Research I

journal homepage: www.elsevier.com/locate/dsri

Physical controls on mixing and transport within rising submarine hydrothermal plumes: A numerical simulation study

Houshuo Jiang*, John A. Breier

Department of Applied Ocean Physics and Engineering, Woods Hole Oceanographic Institution, Woods Hole, MA 02543, USA

ARTICLE INFO

Article history:
Received 30 December 2013
Received in revised form
28 April 2014
Accepted 14 June 2014
Available online 27 June 2014

Keywords:
Hydrothermal plume hydrodynamics
Hydrothermal plume turbulence
Entrainment
Turbulent mixing
Computational fluid dynamics
Turbulence modeling

ABSTRACT

A computational fluid dynamics (CFD) model was developed to simulate the turbulent flow and species transport of deep-sea high temperature hydrothermal plumes. The model solves numerically the density weighted unsteady Reynolds-averaged Navier–Stokes equations and energy equation and the species transport equation. Turbulent entrainment and mixing is modeled by a k–ε turbulence closure model. The CFD model explicitly considers realistic vent chimney geometry, vent exit fluid temperature and velocity, and background stratification. The model uses field measurements as model inputs and has been validated by field data. These measurements and data, including vent temperature and plume physical structure, were made in the ABE hydrothermal field of the Eastern Lau Spreading Center. A parametric sensitivity study based on this CFD model was conducted to determine the relative importance of vent exit velocity, background stratification, and chimney height on the mixing of vent fluid and seawater. The CFD model was also used to derive several important scalings that are relevant to understanding plume impact on the ocean. These scalings include maximum plume rise height, neutrally buoyant plume height, maximum plume induced turbulent diffusivity, and total plume vertically transported water mass flux. These scaling relationships can be used for constructing simplified 1-dimensional models of geochemistry and microbial activity in hydrothermal plumes. Simulation results show that the classical entrainment assumptions, typically invoked to describe hydrothermal plume transport, only apply up to the vertical level of $\sim$0.6 times the maximum plume rise height. Below that level, the entrainment coefficient remains relatively constant ($\sim$0.15). Above that level, the plume flow consists of a pronounced lateral spreading flow, two branches of inward flow immediately above and below the lateral spreading, and recirculation flanking the plume cap region. Both turbulent kinetic energy and turbulence dissipation rate reach their maximum near the vent; however, turbulent viscosity attains its maximum near the plume top, indicating strong turbulent mixing in that region. The parametric study shows that near vent physical conditions, including chimney height and fluid exit velocity, influence plume mixing from the vent orifice to a distance of $\sim$10 times the vent orifice diameter. Thus, physical parameters place a strong kinetic constraint on the chemical reactions occurring in the initial particle-forming zone of hydrothermal plumes.

1. Introduction

Hydrothermal cooling of the ocean ridge system results in the transfer of heat and chemicals from the lithosphere to the ocean (Kadko, 1993; Elderfield and Schultz, 1996; Baker, 2007). The plumes produced by high temperature hydrothermal venting transport significant fractions of this heat and chemicals and interact extensively with seawater (Elderfield and Schultz, 1996). These hydrothermal plumes rise high (100 s of m) above the seafloor (Baker et al., 1995). They are rich in dissolved and particulate inorganic phases and create regions of steep redox gradients that can be exploited by deep-sea chemosynthetic organisms. Numerous studies indicate multiple couplings between abiotic and biotic plume processes including chemosynthetic microbial stimulation (Cowen et al., 1986; de Angelis et al., 1993; Lesniewski et al., 2012), dissolved metal complexation (Sander et al., 2007; Bennett et al., 2008; Li et al., 2014), and organic and inorganic particle aggregation (Dymond and Roth, 1988; Toner et al., 2009; Breier et al., 2012). The coupling of these biotic and abiotic processes has implications for the transport of hydrothermal material; specifically, the extent to which hydrothermal material settles to the seafloor or mixes into the ocean (Bennett et al., 2008; Tagliabue et al., 2010; Breier et al., 2012). The mechanisms by which these couplings occur and the composition and magnitudes of the fluxes involved remain areas of active research.

---

* Corresponding author. Tel.: +1 508 289 3641; fax: +1 508 457 2194.
E-mail address: hsjiang@whoi.edu (H. Jiang).

http://dx.doi.org/10.1016/j.dsr.2014.06.006
0967-0637/© 2014 Elsevier Ltd. All rights reserved.

Fluid physics within the rising portion of hydrothermal plumes strongly influences these topics. It places constraints on the kinetics of transport and mixing, and consequently, the occurrence and rate of speciation, particle-forming, and microbially-mediated chemical reactions. Hydrothermal plume mixing and transport has been described by (i) analytical solutions to simplified conservation equations for momentum, mass, and heat, and (ii) numerical solutions to the Navier–Stokes equations for fluid motion.

Analytical solutions describing plume mixing and transport are based on the classical fluid dynamics theory for one-dimensional time-averaged plume behavior (Morton et al., 1956; Turner, 1973). The theory is based mainly on two assumptions: First, the shapes of mean vertical velocity and mean buoyancy force are similar at all plume heights. Second, the entrainment velocity (U_e) confined in the horizontal direction at the plume edge, which characterizes the rate of entrainment of ambient fluid into the plume, is proportional to the mean plume vertical velocity (W) at that height. Thus, a constant entrainment coefficient, α_e, is defined from $U_e = \alpha_e \times W$. This second assumption is the celebrated "entrainment assumption". Based on these assumptions, simplified conservation equations for momentum, mass and buoyancy are solved analytically for vertical profiles of plume width, vertical velocity and buoyancy. In a stratified fluid, the scaling of maximum plume rise height ($Z_{\max}$) has been given by

$$Z_{\max} = 3.76 \left(\frac{B_{\text{exit}}}{N^3} \right)^{1/4}, \tag{1}$$

where B_{exit} is the source buoyancy flux and N is the ambient buoyancy frequency. The scaling coefficient was determined to be 3.76 by analyzing literature data of observed oil fires in atmosphere and of laboratory plume experiments (Briggs, 1969), but its variability was also noted (Chen and Rodi, 1980). The derivation of this scaling equation also assumed linear mixing behavior and small local variation of density throughout the plume. However, these assumptions are violated by the hydrothermal plume in the immediate vicinity of the vent. This is because the temperature of hydrothermal fluids is much higher than that of the ambient seawater and the equations of state of the high-temperature hydrothermal fluids are nonlinear. Thus, the actual source buoyancy flux (i.e. that calculated using high-temperature fluid density at the vent orifice) cannot be used in Eq. (1). For Eq. (1) to be applicable, it is crucial to use the thermal expansion coefficient of the ambient seawater to calculate a so-called asymptotic buoyancy flux and then use it in Eq. (1) (Turner and Campbell, 1987; Woods, 2010). Moreover, the entrainment coefficient is not constant (Fischer et al., 1979; Chen and Rodi, 1980; Wang and Law, 2002). Nevertheless, the theory has been successfully applied to many hydrothermal plume studies and has produced results that compare favorably with observations (e.g. Converse et al., 1984; Lupton et al., 1985; Middleton and Thomson, 1986; Little et al., 1987; Baker et al., 1989; Cann and Strens, 1989; Speer and Rona, 1989; McDougall, 1990; Rudnicki and Elderfield, 1992; Kim et al., 1994; Stranne et al., 2010).

The Navier–Stokes equation-based numerical approach allows more detailed prediction than the analytical approach permits. It was used to provide information for the plume cap region and exterior recirculation zone where the entrainment assumption is not valid (Lavelle, 1994). It was used to account for two and three-dimensional variations of the plume, such as plume lateral variations (Lavelle, 1994) and spatial variations caused by source spatial distributions (Lavelle, 1995) and by background flow and rotation (Lavelle, 1997; Lavelle et al., 2013). It was also used to study effects of rotation on plume evolution at a relative larger spatial scale and longer time scale (Speer and Marshall, 1995). Time-dependent implementation of the approach also allowed investigating the initial time development and maturation of a plume caused by episodic hydrothermal discharge (Lavelle and Baker, 1994). Specifically, Lavelle (1997) solved numerically the non-hydrostatic Navier–Stokes equations with the Boussinesq approximation and rotation, together with the incompressible continuity equation and the heat and salt conservation equations. Background flow condition and background profiles of temperature and salinity were properly constructed via solving the governing equations in the steady state without heat forcing and under suitable boundary conditions. Turbulent mixing (both horizontal and vertical) was parameterized as the combination of a constant background term and a term represented by an isotropic mixing coefficient. The isotropic mixing coefficient was explicitly dependent on fluid shear, shear Richardson number, turbulent Prandtl number, turbulence length scale and Smagorinsky constant. The equation of state for seawater (i.e. in the low temperature range; Fofonoff and Millard, 1983) was used for fluid properties. An even-spacing Cartesian mesh was used with a 5 m horizontal spacing and a slightly different vertical spacing. The vent condition was modeled by a given heat source spanning two grid cells at the bottom. Although these numerical models did not explicitly include the individual vent conditions (i.e. exit fluid temperature, exit fluid velocity, and vent geometry) and heavily parameterized turbulent mixing, they generated important insights on the effects of background flow, rotation, and three-dimensionality on hydrothermal plume dynamics and pointed out the importance of turbulent mixing in shaping plume development. Recently, Tao et al. (2013) used a turbulent viscosity (μ_t) to model hydrothermal plume turbulent mixing and entrainment more sophisticatedly. The evolution equations of both turbulent eddy size (l) and turbulent kinetic energy (k) were solved to determine μ_t at each grid point and time. Non-uniform Cartesian mesh was used with a 0.59 m finest resolution. The vent condition was explicitly considered by a velocity inlet condition with prescribed high fluid temperature and exit fluid velocity. However, the fluid density was set to be linearly related to temperature. The focuses of all these previous numerical modeling efforts were not on investigating the effects of realistic vent condition and geometry on near vent plume development. Thus, details of model results near the plume stem had to be regarded with caution (Lavelle and Baker, 1994).

The focus of this study is on the near vent plume region because this is where some of the most significant changes in plume chemical composition occur. An important goal of this study is the derivation of scaling relationships that can be used for constructing simplified 1-dimensional models of geochemistry and microbial activity in hydrothermal plumes. The approach used is the generation of a numerical simulation that matches a combination of measured vent geometrical, temperature and fluid velocity conditions, observed by remotely operated vehicle, and measured near vent background seawater temperature and stratification, observed by CTD casts. The simulation is then used to provide estimates of those vent conditions and physical driving forces that are not directly measurable.

Specifically, we use a computational fluid dynamics (CFD) approach to model a hydrothermal plume from the Eastern Lau Spreading Center: A1 vent in the ABE hydrothermal field (Mottl et al., 2011). We employ the k–ε turbulent model (where k is turbulent kinetic energy and ε is turbulence dissipation rate) to represent turbulent mixing and entrainment. We test two different k–ε turbulence closure models for their suitability for hydrothermal plume modeling. We construct a non-uniform triangular mesh to explicitly represent vent geometry. We apply a set of nonlinear equations of state for high-temperature hydrothermal fluids and seawater to represent vent fluid properties as realistically as possible in the near vent region (Sun et al., 2008). We model a baseline plume case using measurements and