Dilution of Dense Bottom Plumes in Turbulent Currents

Petersen, Ole; Larsen, Torben

Published in:
Proceedings of the 4th International Symposium of Stratified Flow

Publication date:
1994

Document Version
Publisher's PDF, also known as Version of record

Citation for published version (APA):
Petersen, O., & Larsen, T. (1994). Dilution of Dense Bottom Plumes in Turbulent Currents. In *Proceedings of the 4th International Symposium of Stratified Flow: Institut de Mecanique de Grenoble, France, June 29-July 2 1994*

4th International Symposium on Stratified Flow
Grenoble June 1994

Dilution of dense bottom plumes in turbulent currents

by

Ole Petersen[1] and Torben Larsen

Department of Civil Engineering, Aalborg University, Sohngaardsholmsvej 57,
DK-9000 Aalborg, Denmark
[1]presently at International Research Centre for Computational Hydraulics at Danish Hydraulic
Institute, Agern Alle 5, DK-2970 Horsholm, Denmark.

Abstract

The dilution of negatively buoyant discharges released into a turbulent current has been studied both in the laboratory and by means of advanced numerical models. The experiments showed that the dilution is mainly due to vertical turbulent mixing and depends on a buoyancy induced dispersion og the plume. These findings have been incorporated into a calibrated integral description of the dilution. A 3-D numerical model with a k-ϵ parameterisation of the turbulent mixing has been applied to the problem and a comparison between this model and the experiments been made. The conclusions are that the dilution can be realistically described by the model.

1 Introduction

Co-flowing negatively buoyant plumes may be formed when dense waste water is continously released from point sources near the bed into a turbulent current, as for example when industrial waste water with large concentrations of salts are released into marine environments. Although the density difference between the discharge and the receiving water may be relatively small, when seen from a hydrodynamical point of view, the nature of these wastes often require that concern is given to the dilution in the immediate vicinity of the discharge. The propagation and dilution of dense bottom plumes may also be of theoretical interest as the situation with a continous release of negatively bouyant water constitutes one of the simpler steady experiments with turbulent mixing across a density interface.

Dense bottom plumes have traditionally been studied in the context of spills of heavy gases in the atmosphere (Puttock et al., 1984; Zumsteg and Fannelop, 1987), while the opposite situation with a light surface plume is more often encountered in the marine environment (Petersen, 1992; Thomas and Simpson, 1985; Weil and Fischer, 1974); a situation which has some similarities with dense bottom plumes.

The aim of the present study is to investigate the dilution of dense bottom plumes. First, a

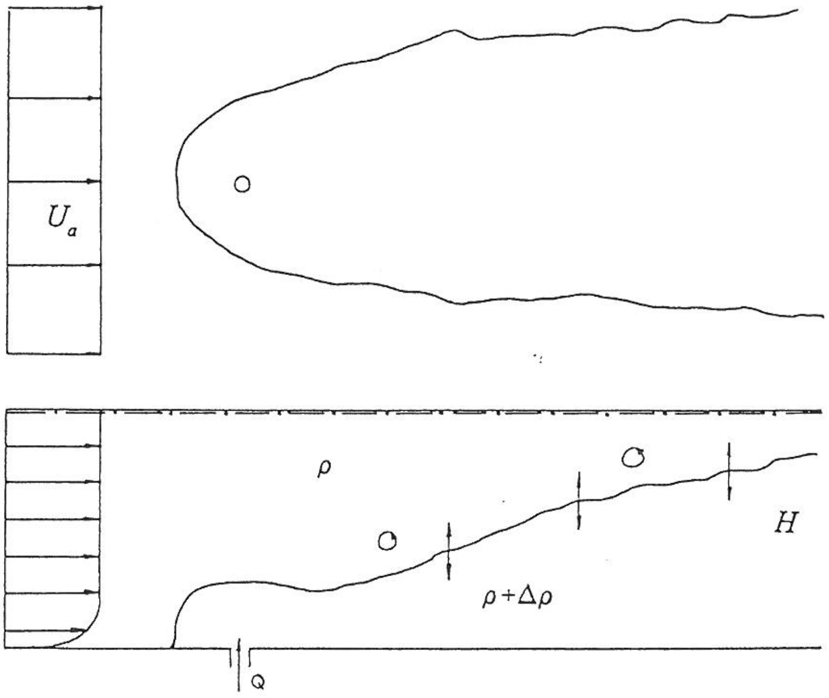

Fig. 1 Dense bottom plume.

series of laboratory experiments is discussed using an idealized integral theory that describes the dilution of the plume. Next, a 3-D numerical model is established and the results are compared to the experiments in order to validate the models in this specific case and to incorporate the data in a more general frame. Finally are the conclusions summarized.

2 Dense bottom plumes

To guide the analysis of the experiments an idealized theory where the dilution depends on a bouyancy induced spread and vertical turbulent mixing is developed below. The distribution of buoyancy in each cross section is characterized by a plume height and width, that both are defined as integral scales. If the local time average density difference is denoted $\Delta\rho_l$, the excess mass m in the cross section may be defined from

$$m=\int\int\Delta\rho_l\,dydz \tag{1}$$

where y and z are lateral and vertical cartesian coordinates, respectively.

The plume height h and width b may be defined from the second moments of the density difference distribution as for example

$$h^2=\frac{1}{m}\int\int\Delta\rho_l\, z^2 dydz \tag{2}$$

for the plume height and similarly for the width. The dilution of the plume can now be described in terms of the downstream development of these cross sectional characteristics. Assuming that the plume is conveyed downstream with the ambient velocity U_a the lateral expansion some distance from the source may be approximated by a bouyancy induced front (Larsen and Sorensen, 1968) with celerity

$$V_f=\alpha\sqrt{gh\Delta\rho/\rho} \tag{3}$$

where x is the streamwise coordinate; g is gravitational acceleration; ρ is the density; α is an empirical correction and $\Delta\rho=m/(8\ m\ h)$. Applying continuity and assuming the dilution to follow a Fickian diffusion law and postulating that the dispersion and the frontal motion are independent the two processes can be combined to

$$\frac{db}{dx}=\frac{V_f}{U_a}+\frac{K_y}{U_a b} \tag{4}$$

$$\frac{dh}{dx}=-\frac{h}{b}\frac{V_f}{U_a}+\frac{K_z}{U_a h} \tag{5}$$

where K_y and K_z are turbulent dispersion coefficients. The vertical dispersion is assumed to depend on the stability through a Richardson number as

$$K_z=K_{zo}/(1+\beta R_{io}) \qquad \text{where} \quad R_{io}=\frac{g}{\rho}\frac{\Delta\rho h}{u_f^2} \tag{6}$$

K_{zo} is the dispersion coefficient in the neutral situation; u_f the friction velocity and β is an empirical factor.

3 Laboratory experiments

The experiments were carried out in a recirculating hydraulic flume, 20 m long and 1.5 m wide, with a flat epoxy painted bed. A dense bottom plume was established by vertically discharging colder tap water with low velocity through a 2.8 cm diameter nozzle located 5.0 m from the downstream end of the flume and in level with the bed. The metered discharge

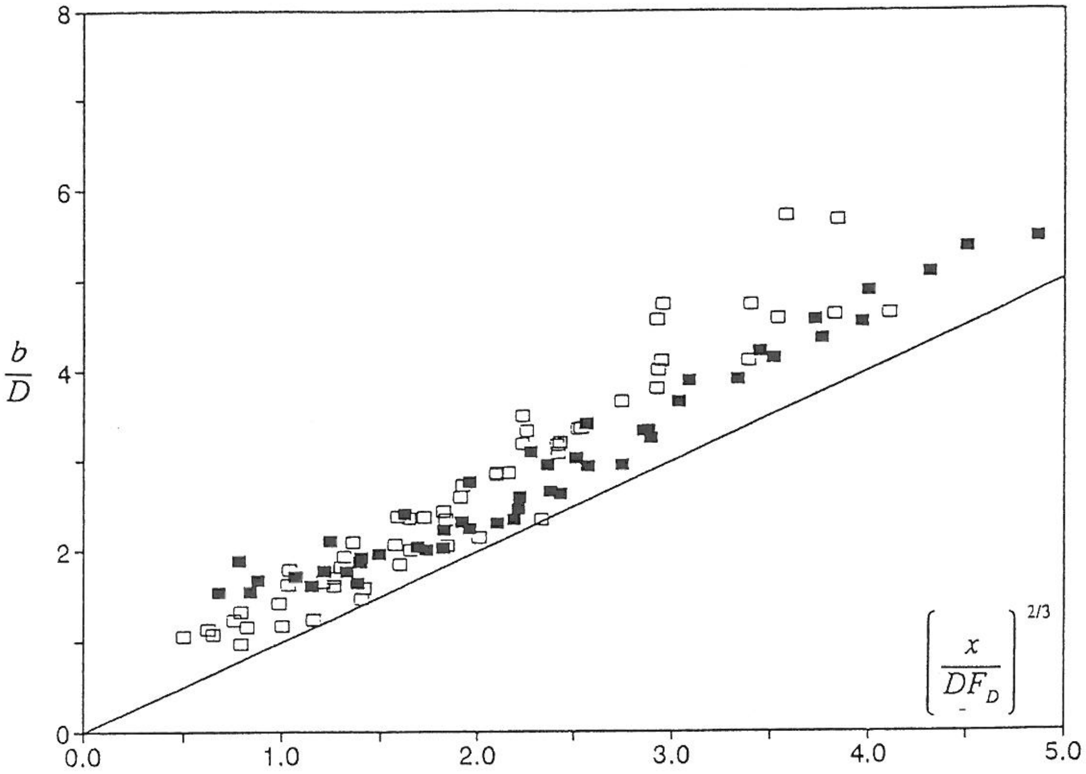

Fig. 2. Measured (open symbols) and calculated by numerical model (filled symbols) relative plume width as a function of a relative downstream distance from the source. The full line corresponds to data from (Weill and Fischer, 1974). Here D is a virtual source diameter and $F_D = U_a / \sqrt{gD\Delta\rho/\rho}$.

went through a storage tank and had a temperature at 6 - 7 °C. The ambient temperature in the flume was app. 18 °C with a drift during experiment at 0.5 °C/hour.
The temperature difference between the plume and the ambient water was measured by means of a vertical array of 8 thermocouples, connected to a PC through an AD converter. The thermocouples were mounted on a step-motor controlled carriage which could automatically traverse the plume. The resolution of the temperature measurement was 0.02 °C and the accuracy of the order 0.05 °C. By means of a standard table implemented on the PC each measurement of temperature was converted into a density-difference in order to allow for non-linearities in the conversion when the temperature fluctuates. Further details of the setup can be found in (Petersen, 1994; Petersen and Larsen, 1992).

4 Results

In each experiment the time average density difference in 15 verticals evenly distributed over the plume cross section was measured in 6 cross sections located with 0.5 m intervals. These

# ()	U_a (cm/s)	H (cm)	T_a (C)	Q_o (l/min)	T_oC (C)
1	7.1	17.0	18.7	4.4	7.1
2	7.1	17.2	18.4	2.1	7.2
3	9.4	17.0	19.0	3.0	7.6
4	9.4	17.0	19.0	4.8	7.5
5	15.0	17.2	18.5	4.8	6.5
6	15.0	17.2	18.3	7.4	6.4
7	20.5	17.0	18.0	9.4	6.6
8	20.5	17.0	17.5	2.7	6.0

Table 1. Experimental conditions

data allowed for a direct estimation of the integral scales the excess mass, the width and the height previously defined. A number of 8 experiment were carried out, covering a range of ambient velocities, discharges and density differences as shown in Table 1. These values ensures that the flow and mixing processes appear as fully turbulent. The downstream development of the plume widths are shown in Figure 2 in a form suggested by Weill and Fischer (1974), which is suitable for immiscible surface plumes (full line). It appears that due to the turbulent dispersion the measured plumes are wider than predicted by the simple theory and that the development of dense bottom plumes largely follows the pattern seen for surface plumes.

The experimental results are reduced by means of a calibration of the integral relations (4) and (5). The transverse dispersion coefficient is found to $K_y = 0.12\ u_f\ H$ from a tracer experiment and the vertical dispersion coefficient is estimated using a numerical model of the downstream development of a neutral plume in a logarithmic boundary layer to $K_{zo}=1.35\ u_f\ h\ (0.57-h/H)$. Summing the difference in the calculated and measured change in dilution between two cross sections the error as a function of the two empirical constants can be estimated. The combination of the constants $\alpha=1.2$ and $\beta= 1.0$ minimises this error and agreement between the calibrated model and the experiments illustrated in terms of the average density difference.

5 Numerical experiments

The dilution in the near field is the result of a 3-dimensional and fully turbulent flow with pronounced buoyancy effects. The mathematical model consists of the 3-dimensional hydrodynamical equations where buoyancy effects are included through an equation of state and a transport equation for temperature. Turbulent stresses and transports are described using an eddy viscosity concept. Boundary conditions are symmetry conditions at the surface

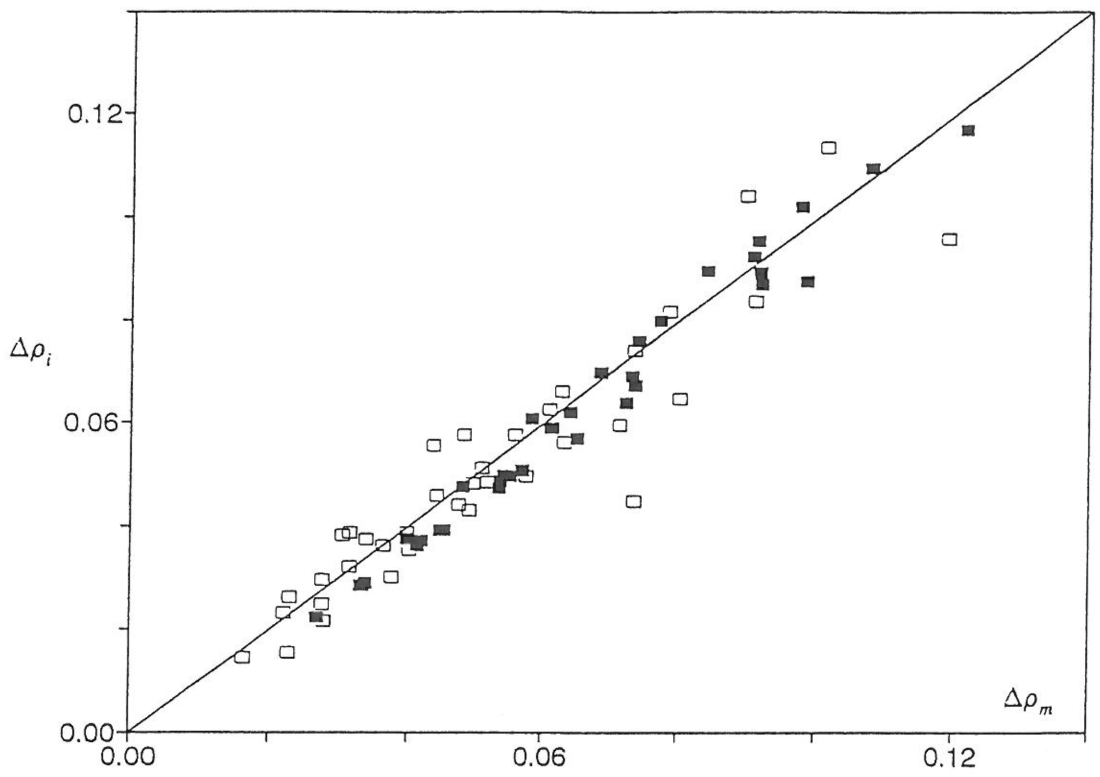

Fig. 3. Density difference obtained from measurements (open squares) or numerical model (filled squares) vs. integral description.

the two sides, prescribed distributions of velocity (logarithmic law) and temperature at the upstream end, simple outflow at the downstream end. The bottom boundary layer is described using a logarithmic wall law. The discharge is here described as a point source of flow and buoyancy, thus the complex details around the discharge is not resolved.
The resulting set of equations are solved using the system Phoenics which is based on a Simple type coupling between pressure and momentum and an iterative solution procedure (Rosten and Spalding, 1987) and here used in combination with a standard k-ϵ turbulence closure. The influence of buoyancy on the turbulence is in the k-ϵ model incorporated as additional sinks in the equations for k and ϵ (see Rodi, 1987). The resolutions used are .06 x .03 x .01 m in the three cartesian directions.

6 Results of the numerical experiments

The theoretical basis for the model has been extensively tested in turbulent boundary layers and also in some cases where buoyancy is important (Rodi, 1987) so only dense bottom plumes will be discussed here. A number of calculations with the k-ϵ model set up as close as possible to the conditions in the experiments has been made and the results treated in a similar manner as the results from the experiments. In Figure 2 are the plume widths from the numerical calculation displayed where it appears that the transverse propagation is reasonably reproduced. In order to verify the dilution the plume scales obtained from the numerical model are used to recalibrate the integral description discussed previously. Following the same procedure as above, this yields $\alpha=1.2$ and $\beta=1.25$. In Figure 3 is the agreement between the numerical model and the calibrated integral description shown; the variance is in this case not due to randomness but can only be attributed to differences between the theories. If the two empirical factors summarize the experimental data the recalibration indicates that the numerical model slightly overestimates the vertical mixing as a larger damping factor β is needed.

7 Discussion and conclusions

The study has examined the dilution of co-flowing dense bottom plumes in a turbulent boundary layer and shown that the dilution can be described as the result of two important factors that are a buoyancy induced spread, which in principle changes the area subject to mixing, and a vertical turbulent mixing that is attenuated by the density gradient.

It has also been demonstrated that a 3-D hydrodynamical model can reproduce these processes.

A general comment is that the study has shown that the dilution depends on a few fundamental processes and as the problem as posed here is steady and has relatively well-defined boundaries it may be well suited as one benchmark case for testing of models for mixing across density gradients.

The more specific conclusions may be summarized as follows :

i) Within the range of ambient velocities and density differences used here the dilution of a co-flowing dense bottom plume can be described using the integral model discussed above, with two constants $\alpha=1.2$ and $\beta=1.0$ both empirically derived in the laboratory.

ii) The numerical model with a k-ϵ turbulence closure gives a realistic description of the dilution.

Acknowledgements

Parts of this work was founded by the Danish National Research Foundation. Their support is greatly appreciated.

Litterature

Larsen, I. and Sorensen, T. (1968). Buoyancy spread of waste water in coastal regions. *Proc. 11th Conf. on Coastal Engrng.*, London, 1397-1402.

Petersen, O. (1994). Laboratory and numerical experiments on the dilution of buoyant surface plumes. in : Davies, P. A. and Valente Neves, M. J. (eds.). *Recent Research Advances in the Fluid Mechanics of Turbulent Jets and Plumes*, Kluwer Academic Publishers, Dordrecht, The Netherlands, 223-236.

Petersen, O. and Larsen, T. (1992). Laboratory study of dispersion of buoyant surface plumes. *Proc. Int. Conf. on Physical Modeling of Transport and Dispersion*, ASCE., Mass., USA.

Puttock, J. S., Colenbrander, G. W. and Blackmore, D. R. (1984). Dispersion results from continous releases of refrigerated liquid. In : Wispelaere, C. D. (ed.). *Air pollution modelling and its applications III.* Plenum Publishers Corp. Ltd.

Rodi, W. (1987). Examples of calulations methods for flow and mixing in stratified fluids. *J. Geophysical Res.*, **92**(C5), 5305-5328.

Rosten, H. I. and Spalding, D. B. (1987). *The Phoenics reference manual.* CHAM Ltd., London.

Thomas, N. H. and Simpson, J. E. (1985) Mixing of gravity currents in turbulent surroundings : laboratory studies and modelling implications. In : Hunt, J. C. R. *Turbulence and diffusion in stable environments.* Clarendon Press, Oxford, 61-96.

Weill, J. and Fischer, H. B. (1974). Effect of stream on heater water plumes. *J. Hydraul. Div.*, ASCE, **100**(HY7), 951-970.

Zumsteg, F. and Fannelop, T. K. (1987). Large scale experiments on the spreading and dilution of cold gasclouds in a controlled environment. In : List, E. J. and Jirka, G. H. (eds.). *Stratified flows.* ASCE, N.Y., 613-622.