Properties of odour plumes from baited traps

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Abstract

The formation of an odour trail can be broken down into a chain of events: First the emission of the attractant from the bait, secondly a turbulent mixing and dilution in the surrounding fluid and thirdly an advection and dispersion of the odour downstream from the source. A simple analysis of the physical processes governing the first two stages indicates that:

- The release of odour will decline as the inverse of the square root of time. The decline curve will be similar for all solid natural baits in a normal size range and soak time.
- Given the diffusion constant in fish tissue just a thin surface layer will release it’s content of odour substances during a fishing operation.
- The initial concentration in the plume will be independent of the size of the bait and only depend on the ratio of surface to cross-section areas.
- To increase the concentration of odour in the plume and utilize a given amount of bait optimally the bait should be cut into relatively small pieces.
- The effect of current speed on the initial odour concentration in the plume is strong. Depending on current variations during the soaking time the effectiveness of the attraction may vary strongly in time.

To extend the analysis and develop models for optimizing the range of the olfactory signal from a bait it is necessary to know the concentration of the attractant in the bait and the threshold concentrations where the target species detect and becomes attracted to the odour trail. When such data become available it will become fruitful to apply existing sophisticated dispersion models for the BBL to practical use for analysis of the range of attraction of baits under different environmental conditions.

Keywords: Odour plume, pots, dispersion, mixing

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**Introduction**

A fish trap or pot requires that the fish encounters the gear. This can be done mechanically using a leader net or by attraction to a signal that is transmitted from the trap. The general properties of the underwater environment are different from our terrestrial experience, which causes difficulties for intuitive grasp of how attraction works. The chemosensory and acoustic senses have evolved in the aquatic environment and are better adapted to water than to air. Everything which is soluble is a potential olfactory stimulus in water, whereas in air this is restricted to the small class of volatile substances. The dispersion in water is slower and an odour trail tends to be detectable over longer time and distances than in air. Acoustic signals spread in all directions and can at the right frequencies be detected at long range. Sound attraction has a large potential but is so far not much used in fishery. Vision is essentially useless other than at very short ranges in the sea. The by far most common mode of attraction is by smell.

The formation of an odour trail can be broken down into a chain of events: First the emission of the attractant from the bait, secondly a turbulent mixing in the immediate surrounding fluid and thirdly an advection and dispersion of the odour downstream from the source. The emission phase has been studied by Løkkeborg in several laboratory and field experiments (e.g. Løkkeborg 1990, Løkkeborg and Johannessen1992 and Løkkeborg and Pina1997). The theory and modelling of plume dilution and dispersion in the third stage is well developed for atmospheric plumes, the result of which in general can be applied also to underwater plumes. Peculiarities pertinent to odour tracking of fish and crustaceans have been reviewed among others by Atema (1987 and 1995), Westerberg (1991) and Moore and Crimaldi (2004).

The purpose of the present study is mainly to look at the first and second phases of the development of a plume in a semi-quantitative way, in order to formulate optimal criteria for baits under different conditions. The third phase and the behaviour of fish to a plume are discussed in more general terms.

**Release of attractant**

The odour from natural bait – a piece of fish or mollusc – is a mixture of soluble organic compounds (Carr et al 1996). Free amino acids have been identified as important food attractants (Hara 2006) but other substances – e.g. peptides, guanido compounds, nucleotides, and organic acids – can be involved.

Inside a dead tissue the transport of such substances is by molecular diffusion alone. The order of magnitude of the diffusion coefficient, $D$, of organic molecules in water is $10^{-10}$ m$^2$/s and will probably at most be the same in fish muscle tissue. A measure of how far a substance has propagated in the tissue by diffusion in the gradient direction and the time $t$ is called the diffusion length, $L_d$, and is defined as

$$L_d = 2\sqrt{D t}$$

A typical size of a bait, $L_d$, is $10^{-2}$ to $10^{-1}$ m and if the ambient velocity, $U$, is $10^{-2}$ to $10^{-1}$ m/s then the residence time, $t_r$, of water surrounding the bait will be in the range 0.1 to 10 seconds.
The ratio between $L_i$ and $L_d$ at time $t_r$ gives a measure of the relative importance of diffusion in the bait and convection on the outside. The square of this ratio is the dimensionless Peclet number, which becomes

$$Pe = \frac{LU}{D}$$

With the parameters above we find that $10^6 < Pe < 10^8$, which means that convection outside the bait is completely dominating and we can assume that the concentration is zero at the bait surface when the concentration gradient inside the bait is calculated. The diffusion in the bait limits the flux of the attractant to the surrounding fluid.

To estimate the actual value of the diffusion coefficient in bait tissues a simple experiment was set up by immersing pieces of bait in a strong colour solution for different times. An approximate value of the diffusion length was found by cutting up the samples and measure the depth of penetration of the dye. The method and results are detailed in Appendix I.

The mean value of $D$ found in this way ranged between $6 \times 10^{-11}$ and $3 \times 10^{-11}$ m$^2$/s for the tested bait types. A characteristic value can be taken as $4 \times 10^{-11}$. This allows us to calculate the diffusion length as a function of time, which also is a measure of the thickness of the layer of a bait that will contribute in forming the odor trail. The result is shown in Figure 1.

For a piece of bait which is say $3 \times 3 \times 3$ cm in size we find that just about 50% of the bait has contributed to odor emission after 24 hour soak time. It will take more than a week until the odor substances at the core of the bait reach the surface.

![Figure 1](image-url)

**Figure 1.** The thickness of the surface layer of a natural bait which contributes to formation of an odor plume as a function of soak time.

Immediately after submersion of the bait, at times $\leq t_r$, the flux of odor substances depends on rapidly changing diffusion processes both inside and outside the bait surface. When $t \gg t_r$,
and as long as the diffusion is limited to a thin layer inside the bait surface we can neglect effects of the actual shape of the bait and the local flux, $J$, is determined by Fick’s law:

$$ J = -D \frac{\partial c}{\partial n} $$

Where $n$ is a coordinate in the direction perpendicular to the surface and $c$ is the concentration of the substance. As discussed above convection will hold the concentration to zero at the surface. With the assumptions that the bait is large compared to the diffusion length during the whole soaking time the characteristic length of the concentration gradient becomes equal to the diffusion length, which means that we can make the approximation

$$ J \approx -D \frac{c_0}{L_d} = -\frac{c_0}{2} \sqrt{\frac{D}{t}} $$

where $c_0$ is the initial concentration in the bait tissue.

As $c_0$ and $D$ are constants this means that the flux of odour from large baits depends only on time and follows a simple and universal decline with $t^{-1/2}$. Figure 2 show the flux expressed relative to an arbitrary initial value chosen as the flux at 1 minute after submersion.

![Figure 2](image-url)

Figure 2. Relative rate of emission of an odour substance from a natural bait as a function of soak time.

This time dependence of the rate of release is also found in the experiment made by Løkkeborg (1990). Figure 3 shows his data compared to a decrease calculated with a $t^{-1/2}$ law.
Figure 3. The observed rate of release of amino acids from a mackerel bait determined by fluorometry in running sea water (Løkkeborg 1990) compared to the theoretical decrease calculated from the observed rate at 1 hour and following a $t^{-1/2}$ dependence.

There are two main conclusions from the analysis so far:

- The release of odour will decline as the inverse of the square root of time. The decline curve will be similar for all solid natural bait in a normal size range and soak time.
- Given the observed diffusion constant just a thin surface layer will release it’s content of odour substances during a fishing operation (approximately 3 mm in 12 hours).

The implication is that a large part of baits are wasted. The optimal shape of a bait would be one with a large surface to volume ratio and a characteristic cross-section approximately equal to the diffusion length based on the intended soak time. An earth-worm may be close to the ideal.

Another implication is that the release of odour will increase sharply if fresh surfaces are exposed on the bait, e.g. if a fish takes a bite out of it.

**Initial dilution of the attractant**

As found above the release of odour substances is a time-dependent phenomenon which for large bait will occur at the same rate $J$ over the whole surface. The total surface area, $A$, times the flux $J$ gives the source strength or emission, $H$, from the bait:

$$H = Ac_0 \frac{\sqrt{D}}{2\sqrt{t}}$$

The odour will mix continuously into the water current flowing past the bait. The character of this mixing process will vary depending on the turbulent intensity in the current. If the eddy velocity at the length scale of the bait is low compared to the mean current velocity then the
bait can be seen as an obstacle which generates vortices and intensified mixing in the downstream wake. The odours swept off from the bait will feed into this mixing zone and become diluted.

A simple model to estimate the starting value of the diluted odour concentration in the plume is that the odour will become homogenized within the wake a relatively short distance downstream of the bait and that the cross-section of the wake is approximately the same as the cross-section of the bait. The turbulence in the wake of a sphere is fully developed 100 to 500 diameters downstream (Townsend 1949). The diameter of the wake grows slowly and is proportional to the cube root of the downstream distance (Johansson and George 2006). If the cross-section of the bait is denoted \( B \) those assumptions lead to the following expression for the initial odour concentration \( c_i \):

\[
c_i \approx \frac{H}{UB} = \frac{A c_0}{2 UB} \sqrt[3]{\frac{D}{t}}
\]

The initial odour concentration in the plume will thus be proportional to the odour concentration in the bait and inversely proportional to the current velocity. It will decline as time \(-\frac{t}{2}\). An important observation is that

- The concentration will be independent of the size of the bait and only depend on the ratio of surface to cross-section area

For a single piece of bait the surface to cross-section ratio, \( P \), will have a minimum of 4, which is that of a sphere. Any more irregular shape gives larger ratio, e.g. for a cube it is 6. For asymmetric shapes the ratio will depend on the orientation also. However, the most obvious way to increase the \( P \) is to divide the bait into smaller pieces. This will both increase the concentration of odour in the plume and utilize a fixed amount of bait better.

To illustrate the effect of cutting up the bait we can construct a simple example, where a cube is cut in half, each piece again cut in half across the longest side and so on. The pieces are packed randomly, which means that the package will have a somewhat larger cross-section than the original cube – say 20% larger. The result of this exercise is shown in Figure 4.

With three cuts, resulting in eight pieces, the surface to cross-section area and the plume concentration has almost doubled. With six cuts the concentration is three times higher. The diagram shows the 6 first cuttings. If the original piece has a side of 6 cm then the smallest pieces will have a dimension of 1.5 cm, which still is large compared to the diffusion distance after 24 hours.

The conclusion is that:

- To increase the concentration of odour in the plume and utilize a given amount of bait optimally the bait should be cut into relatively small pieces.
Figure 4. The surface to cross-section area ratio for a bait which is successively cut into smaller pieces and loosely packed in a bait bag. This ratio is also proportional to the initial odour concentration in the plume.

Besides $P$ the other parameters that determines $c_i$ is the ambient current velocity and time. The time dependence is a steady decrease of emission following a $t^{1/2}$ law as has been discussed above. The initial dilution is inversely proportional to the current velocity, which means that the variation can be quite large at weak currents but becomes less sensitive to fluctuations when currents are strong.

In the coastal environment where traps and pots are used diurnal and semi-diurnal tidal currents tend to dominate the velocity field. Even in areas with weak tides, as the Mediterranean or the Baltic, currents are seldom steady for long periods. Passing weather systems will generate transient currents and long-period waves with time-scales that seldom exceed a day.

To illustrate the effect of current variations on the odour concentration in the plume we can calculate the time development of $c_i$ when the pot is deployed at different times during a semi-diurnal tidal cycle. The result is shown in Figure 5.

In this example the current is never allowed to go to zero. The minimum current in the tidal ellipse is put to 10% of the maximum. Nevertheless the effect of the current speed on the initial dilution is such that the maximum plume concentration occurs at slack tide several hours after the setting of the gear if setting is done at another phase of the tide.
The conclusion from this is

- The effect of current speed on the odour concentration in the plume is strong and the time of setting the gear can be important. Depending on current variations during the soaking time the effectiveness of the attraction may vary strongly.

Evidently the current speed not only determines the initial concentration, it is also the determining factor for the downstream advection of the odour and the range of attraction of the bait.

**Formation of the odour plume**

The initial dilution in the wake occurs in a short distance, of the order of magnitude $10^2$ to $10^3$ bait diameters downstream of the bait. Subsequent to this the odour is subject to a continuous dispersion and diffusion by turbulent eddies of the same or smaller size than the odour cloud and to advection by the mean current and larger eddies. This will result in a meandering and gradually expanding plume with decreasing odour concentration, similar to the smoke plume from a chimney.

The detailed development of the plume depends on several widely variable conditions, that will differ between times and places where a pot or trap is used. Important factors are the velocity and shear of the current, the turbulent intensity at different spatial scales and if the fluid is density stratified. There is a vast literature on the subject, some basic texts are e.g. Csanady 1973, Okubo and Levin 2001. Some general observations relevant to understanding odour plumes from baited pots will be given here, but it is outside the scope of this paper to cover plume formation in any detail.
Much of the theory and modelling of plumes is based on a steady-state statistical description of the concentration at different points in the plume. Such models are called Gaussian dispersion models and the output is typically a normal distribution of the concentration of the odour in a plane perpendicular to the current direction and the plume centred along a straight axis in the mean current direction.

For a particular point downstream from an odour source a Gaussian model describes the long-time average concentration. This has little or no relevance for understanding the detection and orientation of a fish to the plume in a natural environment. What a fish is able to perceive is the instantaneous realization of the plume, which is a much narrower, meandering odour cloud that can be broken up in discrete patches (Balkovsky and Shraiman 2002, Ormerod 2001). Figure 6 illustrates the difference between the Gaussian representation and the instantaneous realisation of a plume.

Figure 6. A conceptual sketch of a Gaussian plume model (below) and the instantaneous picture of the same plume (above).

The important points are that:

- A Gaussian plume model strongly exaggerates the local dilution of the odour concentration at a downstream point in a plume.
- In a fixed position far enough downstream the odour signal will be absent most of the time. When an odour patch arrives it will be perceived as a burst with strong concentration fluctuations.
- There is no simple relation between the local current direction in an odour patch and the direction to the source.
An odour plume from a fishing gear is time dependent also in the sense that it will have a starting time \( t=0 \) when the gear is set. The plume then grows downstream in length as it is advected by the mean current \( U \). The downstream distance \( x \) and the time \( t \) since the initiation of the plume are connected by the simple relation \( x=Ut \). This expression shows the total length of the plume after time \( t \) but can also be used to describe the equivalence between the development time and downstream distance for any patch in the plume.

The local concentration in an odour patch will decrease with time due to dispersion. Dispersion can be defined as the combined effect of diffusion and shear, where diffusion means the mixing with the surrounding fluid by turbulent or molecular movements. Shear is the spatial rate of change of the velocity, which causes deformation and stretching of the patch. The rate of dispersion depends on the intensity of mixing and shear. There are abundant experimental data from the release of dye or drogues in the surface mixed layer in coastal waters (Stommel 1949, Hayakawa 2003).

Okubo (1971) has derived empirical relations between diffusion characteristics and the time and length-scales for dye-release in the mixed layer. He finds that the horizontal variance of a patch \( \sigma_{re}^2 \) increases somewhere between \( t \) to the power 2 or 3. A fit to the data gives \( t^{2.34} \). The scale of diffusion is taken as \( 3\sigma_{re} \) which, if the patch is symmetric and the concentration has a normal distribution radially, means that 95% of the odour is found within the diameter \( 3\sigma_{re} \), which also is applicable to the instantaneous plume width. Using the values presented by Okubo and applying a mean current velocity of 0.1 m/s we get a distance-to-width diagram of a plume shown in Figure 7. The time after the start of plume development is indicated in the diagram and the plume width at these times will be the same independently of the current velocity, but the distance scale will be different.

![Figure 7. Width of a plume calculated from the empirical dispersion characteristics compiled by Okubo (1971). The distance scale is based on a current speed of 0.1 m/s.](image-url)

Those data are for a 2-dimensional dispersion in a bounded surface layer where the turbulent mixing is likely to be higher than in deeper water. The calculation should be seen as an upper extreme case of the dispersion. The assumption of 2-dimensionallity is also questionable but
may be acceptable in a stratified case where the turbulence is strongly anisotropic. With those caveats we can use the same data to estimate the concentration as a function of time or distance downstream. We then find that after 1 hour the mean patch concentration will be of the order of magnitude \(c_i 10^{-5}\) and will decrease with a further factor of 10 after 3 hours. It should be noted that the peak concentration in the patch can be substantially higher however.

In practise the plume from a pot will usually form close to the bottom. This is in a hydrodynamic regime where the current velocity decreases to zero at the bottom and the vertical turbulent eddies are limited in size by the distance to the bottom. This so called benthic boundary layer, BBL, can be divided into a thin viscous and laminar sub-layer at the very bottom and an outer Ekman layer influenced by the rotation of the earth. In between the flow is unaffected by the rotation of the earth and the mean velocity increases logarithmically with height (Wimbush and Munk, 1970, Bodreau and Jørgensen 2001). This layer is characterised by a constant vertical shear stress and is called the logarithmic layer. The thickness in coastal waters is typically 1 to 10 m, which means that this is where odour plumes from baits commonly will be found.

In the logarithmic layer the dispersion is dominated by a combination of vertical eddy diffusion – which increases linearly with height, \(h\), above the bottom – and the current shear – which decreases with height. The local dispersion in the BBL will decrease with height above the bottom as \(h^{-1/2}\) and increase with time as \(t^{3/2}\). A general observation that can be made from this simple analysis is that

- Dispersion of an odour plume in the BBL is larger if the source is closer to the bottom
- The downstream advection speed decreases rapidly towards the bottom.

**Discussion**

A simple analysis like this of the physical processes involved in the formation of odour trails from bait can be useful. It identifies which properties of the bait and in the environment that is important to define the properties of the plume. Crucial point found in the analysis are the rapid decline in odour source strength and the low efficiency in utilizing the active substances in natural baits. This emphasizes the importance of developing alternative delivery systems. It should be possible to design artificial baits so that the emission rate is constant or even better proportional to the ambient current velocity, which would give a constant initial odour concentration in the plume. For natural baits the Norbait concept, using waste fish and offal in a gel, seems to answer some of the problem. What is desirable is a method which successively sheds off the surface layer of the bait in a controlled manner.

To extend the analysis and develop models for optimizing the range of the olfactory signal from a bait it is necessary to know both \(c_0\) in the bait and the threshold concentrations where the target species detect and becomes attracted to the odour trail. Much experimental data exist on detection and search activation thresholds to different chemical stimuli (Døving 1986, Hara 1994). Measurements of \(c_0\) or \(c_i\) are essentially lacking however. When such data become available it will be fruitful to apply the existing more sophisticated dispersion models for the BBL to practical use in analysis of the range of attraction of baits under different environmental conditions.
The focus of this paper is on the dispersion of the odour plume. Evidently the diminishing concentration is decisive for how far downstream an odour can be detected by a fish, but there are other properties that may be equally important. Any information that a fish can extract on how old the trail is or how far away and in which direction the source is to be found must be advantageous in deciding if it is worth starting a search. Some work on this question has been done in insects (Murlis et al 1992) and in crustaceans (Weissburg and Zimmer-Faust 1994). Essentially the finding is that the animals integrate some form of chemically modulated orientation (chemotaxis) with a visual or mechanical assessment of flow conditions in order to move upwind (rheotaxis). Across-stream turns – zig-zaging or casting – are typical features of the tracks (Vickers 2000). It is characteristic that the animal receives short intermittent bursts of odour concentration and temporal analysis of the signal can be used to infer spatial gradients. No similar detailed experiments have been made on fish behaviour in intermittent plumes under realistic conditions. Such studies can give a better understanding of what properties of an odour plume are the most significant from a fishery technology point of view.

References

Hara, T.J. 1994. The diversity of chemical stimulation in fish olfaction and gustation. Reviews in Fish Biology and Fisheries. 4:1-35
Løkkeborg, S. 1990. Rate of release of potential feeding attractants from natural and artificial bait. Fisheries Res. 8:253-261.
Appendix 1 – Determination of molecular diffusivities in fish tissue

Introduction

The rate of release of attractant compounds from fish baits will be determined by the mass-transport rates inside of the bait and in the surrounding liquid. Mass transport in the fish tissue is by diffusion only and on the outside by diffusion and convection. As diffusion is much slower than convection, the inner mass-transport will determine the release rate.

Any water-soluble compound in the fish tissue can act as an attracting odour; free amino acids, small peptides, nucleotides or organic molecules. In order to get an estimate of the molecular diffusivities in fish tissues samples of bait were immersed in a dye solution, the dye molecules acting as model-molecules for the odour compounds. The penetration depth of the dye was measured in a cross-section of the bait after varying time intervals. Assuming that adsorption and capillary effects could be neglected, the penetration depth could be taken as equal to the diffusion length \( L_d \) and the diffusivity \( D \) in of the dye calculated as:

\[
D = \frac{C_d}{4t}
\]

Material and methods

Materials

The baits tested were fresh and frozen whiting (Merlangius merlangus) and mackerel (Scomber scombrus), frozen tiger prawn (Penaeus monodon) and frozen small octopus (Octopus dolfusi). Frozen baits were defrosted prior to the experiments. Two dyes were used, 10 g/L Rhodamine B and 5 g/L Methylene blue. The molecular weights of Rhodamin and Methylene blue are 380 and 310 g/mole respectively. The molecular weight of free amino acids range between 100 and 200 g/mole.

Experimental setup

The baits were suspended in dye solution and stirred with a magnetic stirrer (250 rpm), Figures 1 and 2. The dye was allowed to penetrate the bait for time intervals of 1-24 hrs, Table 1. The baits were taken out of the dye bath, rinsed in water and dried on the surface before making an incision perpendicular to the cut surface of the bait. In this cross-section a penetration front of dye was quite clearly distinguishable. The skin of the fish was likely to act as a barrier against mass transport and the penetration depth was therefore only measured from the cut surface of the bait sample, see Figure 1. The samples were photographed together with a mm scale and the distance from the cut surface to the dye front was measured at several points and averaged using the Bersoft Image Analyse software, Figure 3.
Figure 1. The baits before dying. Mackerel (left) and whiting (right).

Figure 2. The experimental setup with Rhodamine solution.

Figure 3. Cross-section of whiting (left) and mackerel (right) after immersion in dye for 4 hours. The penetration depth is measured perpendicular to the original cut surface.
Table 1. Summary of the experiments.

<table>
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<th>Sample</th>
<th>Dye</th>
<th>Time (s)</th>
<th>Penetration (mm)</th>
<th>Standard dev</th>
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Result

The calculated effective diffusivities are reported in table 2 and figure 4 below. The calculated diffusivities were higher for the measurements performed over shorter time periods. The uncertainty if the measurements for shorter experiment times were also larger and effects such as creeping of dye on the fresh incision surface can be expected to have a larger influence on the experiments with shorter exposure times and therefore smaller penetration depths. Another possible explanation is initial adsorption at the bait surface.

Table 2. The experimental results and calculated diffusivities, D, in m²/s. D+ and D- are values for the diffusion coefficient calculated from the mean penetration depth + and – one standard deviation respectively.

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Figure 4. The calculated diffusivities for the samples as a function of exposure time.