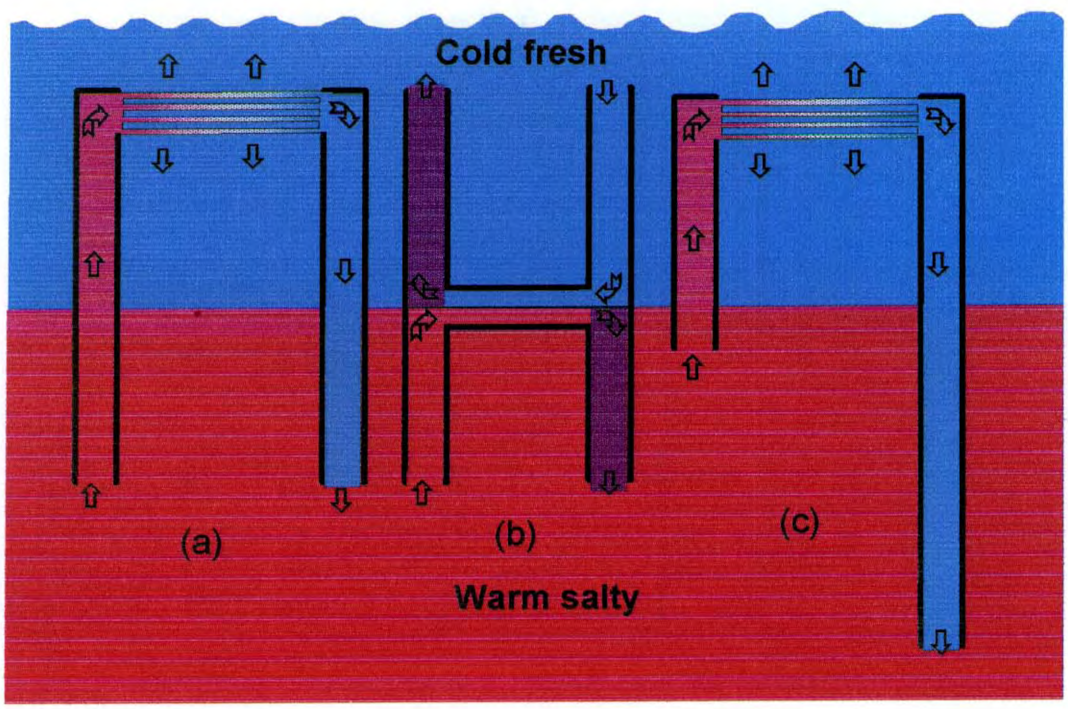
REPORT SNR 3776-98

Artificial pumping of seawater in fjords

A preliminary feasibility study of a self-sustained diffusive pump



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Abstract
A previous theoretical study showed that it is possible to generate and maintain a significant flow of seawater inside specifically coiled tubes that vertically extends across the pycnocline in stratified waters such as fjords. This report focus on possible applications of this principle, by means of the "diffusive pump". It describes the different environments in which the pump may be used and how the pump may act to change the oceanographic conditions there. Electricity production is one application, but the report elaborates more on other uses, such as on stimulating the vertical convection and water exchange, improving water quality, and various use in aquaculture. Separate small-scale tank tests of the pump have recently been successfully performed at Dartmouth College in the USA, and it is suggested that more joint research and follow-up tests, including a prototype test in a fjord, should be the next steps, following this preliminary feasibility study.

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1. Fjorder	1. Fjords
2. Fornybar energi	2. Renewable energy
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4. Kunstig oppstrømming	4. Artificial upwelling

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Artificial pumping of seawater in fjords.

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a self-sustained diffusive pump.

Preface

This brief report is a follow-up of a theoretical study published in 1992 on a self-sustained pump that can extract potential energy from seawater. The report points at some possible future applications of this concept in fjords, and the feasibility of such applications.

Prof. B. Cushman-Roisin at Dartmouth College in New Hampshire who originally participated in the theoretical development contributed with interesting information about a recently performed laboratory test on the pump.

This study was funded by the Norwegian Research Council through the 50,000 NOK grant No 31800-31 in 1996 from the NYTEK programme which promotes studies on effective and renewable energy technologies. Dr. Fritiof Salvesen at *KanEnergi AS* was NYTEK's contact person.

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Bergen/Oslo, August 1998

Lars G. Golmen

Contents

Summary

Creating artificial upwelling and exploiting of thermal differences in the tropical ocean have been studied for decades in connection with mariculture and power generation for various applications. The concepts developed will not, however, operate under oceanographic conditions found in regions of the cold water hemisphere.

This report describes one means of creating similar upwelling in fjords which have different stratification and where the flow is contained within a floating or submerged device of vertical and horizontal tubes, named a '*diffusive pump*', which actually will maintain a self-sustained flow inside it. This flow may drive an electric generator, or can be applied for other uses such as:

- Pumping of oxygen-rich surface water into deep, anoxic waters for use in fjord restoration
- Bringing nutrient-rich deepwater to the productive euphotic layer to enhance bioproduction (mariculture)
- Pumping of warmer deepwater to the surface layer to hinder or delay ice formation during cold spells in winter
- Flushing of the surface layer near or inside aquaculture farms to enhance the water renewal

It has previously been calculated that a pump device of modest size (radiator area of 10x10m) can produce 1 kW of power or more, and generate a flow on the order of 1 m^3/s under normal winter conditions. Recently laboratory tests have been performed successfully in USA. But so far, no prototype installation has been made, and the report discusses how this could be achieved, via a set of steps that includes

- Selection of a suitable site (fjord)
- Oceanographic measurements at the site, to get sufficient background data
- Computer simulations of the various devise designs, to maximize flow
- Assessing the possible negative environmental impacts from the operation of a pump

There is a growing trend internationally to explore new energies. It its envisaged that further studies of the diffusive pump may gain support both from companies, governments and institutions that are engaged in such research.

1. Introduction

1.1 Background and motivation

The concept of creating artificial upwelling or exploiting thermal differences in the tropical ocean has been studied for decades in connection with mariculture and power generation for various applications. Much of this activity derives from the paper by Stommel et al. (1956) who showed that a flow can be maintained within a vertical pipe extending from surface waters to deep waters in the tropical ocean if the flow is subject to some initial priming. The modern parallel to this is the OTEC (Ocean Thermal Energy Conversion) which was launched in the 1970-ties and where several full-scale experiments have been performed (Avery and Wu 1994).

One way of creating similar upwelling in fjords which have different stratification and where the flow is contained within a system of vertical and horizontal tubes has been described by the present author and Prof. Benoit Cushman-Roisin in a paper from 1992 (Golmen and Cushman-Roisin 1992). That paper gave a theoretical presentation of the concept, and a few adaptations were discussed, but in no detail. Some possible applications in fjords were also suggested, but the study was not followed up due to lack of priority and funding, although a summary of the concept was given by Golmen (1995).

In the last few years the focus on the world energy situation has steadily intensified. It is recognised that the most important energy production by burning of fossil fuels are causing an increase in the greenhouse gas CO_2 in the atmosphere, which can have adverse global environmental effects in the long run (IEA 1995). Due to the concern about this, there has been a growing interest in exploring new energy sources, and efforts spent on research on new energies are probably exceeding similar efforts made in the early seventies, during and after the oil crisis which peaked in 1973.

The international energy agency (IEA) is an important promotor of such research. Many countries has developed their own organisations and programmes to pursue development of alternative or new energies.

1.2 Research on alternative energies in Norway

Due to the dominance of hydroelectric power production in Norway, research on alternative energies has traditionally been neglected. But this now seems to change due to new developments in this area internationally incl. the efforts to reduce greenhouse gas emissions. The research and development on new and environmentally friendly energies is mostly promoted by the government and the Norwegian Research Council (NFR) but some private companies are also active.

In 1993 NFR launched a new program on heat pumps, on which there already was some ongoing research activity, mainly undertaken by SINTEF. The NYTEK programme (on 'Effective and renewable energy technologies') which supported the present study to promote research on new energies was launched by NFR in 1995 (NFR 1995) and in 1997 another 5 year programme on energy/electricity use including some focus on renewable energies emerged. NFR's KLIMATEK programme began in 1997, to promote development of technologies to reduce greenhouse gas emissions. The larger oil and industrial companies will have their own development programmes, as is the case for many multinational enterprises.

Several feasibility studies such as on heat pumps (Fredriksen et al 1990) and Reverse osmosis (salinity gradients, Thorsen 1996) have emerged recently. Presently there are large on-going efforts to explore wind power in Norway. The present report may be looked upon as a study on exploiting another "new energy", i.e. the source of potential energy stored in the stratified waters of fjords and similar locations.

1.3 The international perspective

R&D on alternative energies has increased internationally during the present decade. It may seem as a rejuventation of similar research conducted in the early 1970's, during and after the 'oil crisis' which peaked in 1973. The present background may, however be somewhat different. Scarcity of fossil fuels is not a forefront topic today. In stead, there is growing concern about the greenhouse effect and global warming mainly due to the anthropogenic emissions from burning of fossil fules (coal, oil, see IPCC, 1995). This has called for actions to introduce 'cleaner' energies, e.g. as part of the CTI (Climate Technology Initiative) umbrella of the IEA.

The diffusive pump, although probably of minor importance to solve general problems, may be one of many technologies that can stimulate positive thinking in the right direction, and that in certain areas may actually be of significance either as energy supplier or energy converter.

2. Review of the *diffusive pump* concept

2.1 Background

It has been known for a long time that under certain hydrographic conditions it is theoretically possible to maintain a continuous vertical flow of seawater in a tube crossing the pycnocline in the ocean. The flow is driven purely by a potential energy exchange with the water column surrounding the tube. This principle was first treated theoretically by Stommel et al. (1956), who presented their "perpetual salt fountain". The working principle is based on the water inside the tube loosing, or gaining buoyancy by lateral diffusion of heat, but not salt, through the tube wall. They argued that a flow in a thermally conductive tube extending from the warm and salt surface layer into the colder and fresher deep water would, after initialization, be selfsustained, i.e. with no need for pumps. Stommel et al. even suggested that this principle could be used for pumping up nutrient rich deep waters into the surface layer to enhance biological production there.

The note by Stommel et al. was followed by a feasibility study (Groves 1959). Employing a model for tube flow, which included tube resistance, Groves indicated that a small, but significant vertical flow of water could be maintained in regions where warm salty water overlies colder fresher water. However, Groves maintained the view of Stommel et al. that the tube was nothing but an "oceanographic curiosity".

The idea of Stommel et al. (1956) is based on the combined and opposite effect of temperature and salinity differences on sea water density. During the past decades substantial work has been done to design devices for extracting energy from temperature and salinity gradients. This includes work under the OTEC (Ocean Thermal Energy Conversion) program in the U.S., which focuses on the significant temperature difference between surface and deep water in temperate and tropical zones of the ocean, essentially using the Rankine Cycle (heat exchangers) (Isaacs and Schmitt 1980, Kinelski 1985).

Salinity gradients represent a fairly recently recognized potential source of energy. The osmotic pressure difference between sea water and fresh water constitutes a remarkable energy source, provided that sufficiently efficient semipermeable membranes can be designed. (Wick 1978, Isaacs and Schmitt 1980).

To our knowledge, however, no device has been specifically designed to work on the principle of the before mentioned "salt fountain". There are reports, however, on 'accidental' self-initiated flow within long tubes used for exploiting manganese nodules on the deep sea bottom which probably is caused by the same principle.

The paper by Golmen and Cushman-Roisin (1992) recaptured the basic working principle of the "salt fountain", and stated that a modified device theoretically could work also under conditions different to the ones found in equatorial waters. Next they suggested various designs of field "units" that might be applied in fjords, with some estimates for the power output under various hydrographic conditions which may be found in many fjords and bays with shallow sills at the entrance. Figs. 2.1 and 2.2 depict different conceptual shapes of the diffusive pump.

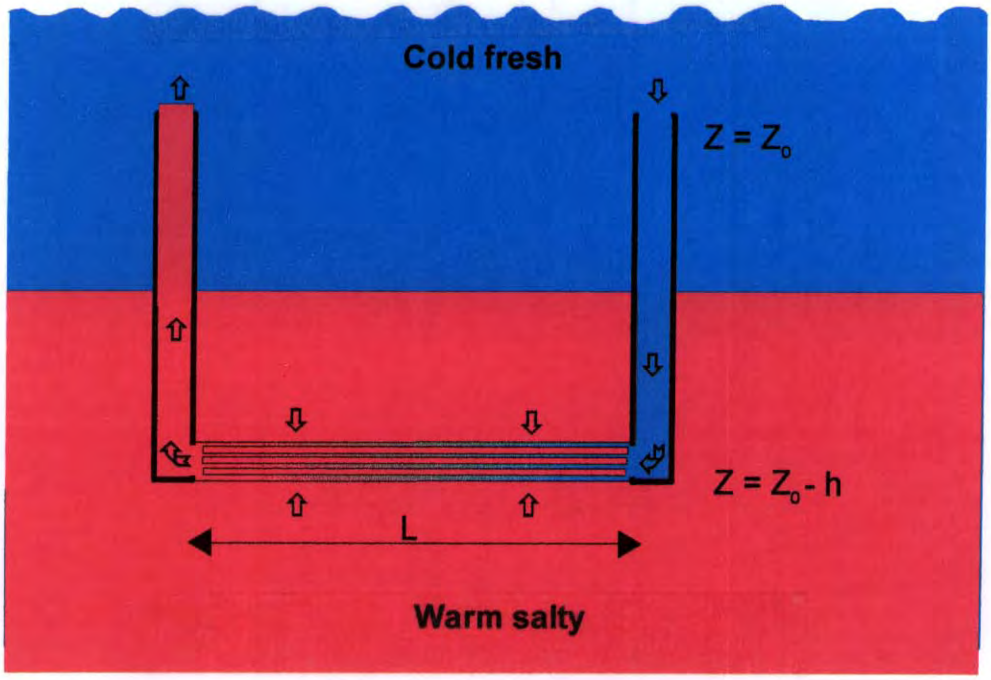

Fig. 2.1. Conceptual sketch of a simple "U" tube design, extending across the pycnocline. Cold, low-salinity surface water is drawn through the radiator which is placed in the warmer deepwater. Heating of the water flowing in the tube reduces its density and this will maintain an upward flow in the left tube.

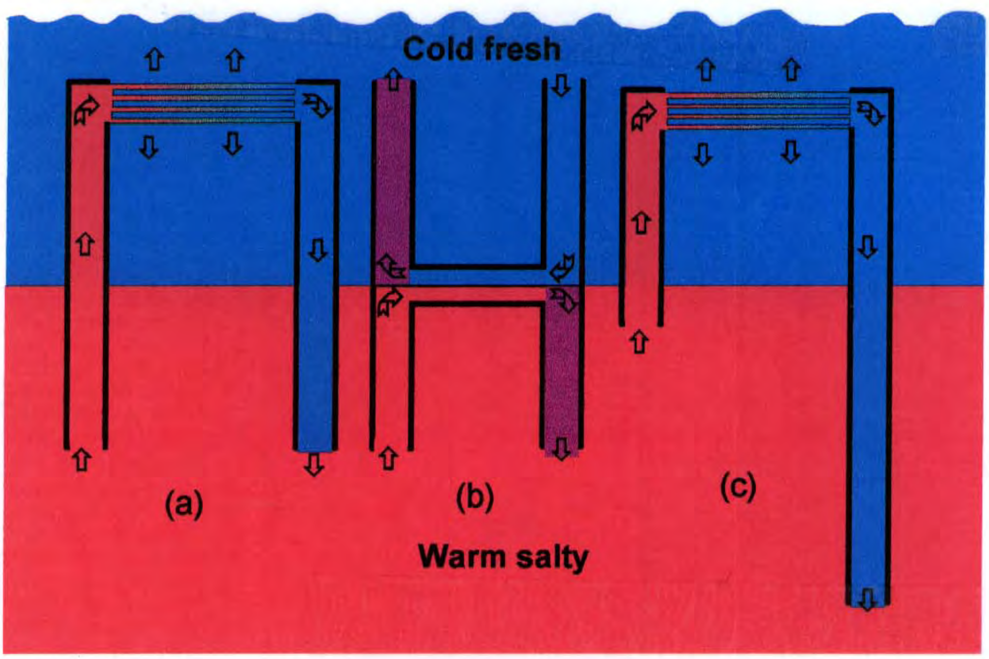

Fig. 2.2. Some alternative designs of the tube and radiator assembly.

The previous study suggested various uses of the diffusive pump, such as

- pumping of oxygen rich surface water into deep, anoxic waters for use in fjord restoration
- Bringing nutrient-rich deepwater to the productive euphotic layer to enhance bioproduction (mariculture)
- Pumping of warmer deepwater to the surface layer to hinder or delay ice formation during cold spells in winter
- Flushing of the surface layer near or inside aquaculture farms to enhance the water renewal
- Electric power generation

2.2 Theory

Several theoretical issues related to the pump has already been described in the previous paper from 1992. Therefore only a brief recaption is made here.

When calculating the efficiency of the pump, it is essential to have numerical expressions describing the ambient stratification, i.e. the vertical distribution of sea water density, ρ (z), which is a function of salinity, S and temperature, T (we ignore the pressure dependency of density, i.e. regarding seawater as incompressible.):

1) $$\rho(z) = \rho_0[1 - \alpha(T - T_0) + \beta(S - S_0)].$$

α and β are the thermal and haline (positive) expansion coefficients and T_0 and S_0 are the local values of temperature and salinity at level z_0.

The vertical ambient temperature distribution is given by

2) $$T(z) = T_0 + a(z - z_0),$$

and likewise the vertical salinity distribution may be given as a linear expression by

3) $$S(z) = S_0 + b(z - z_0),$$

where a and b are the local vertical gradients ($\partial T/\partial z$, ($\partial S/\partial z$) of temperature and salinity.

These expressions may be combined into:

4) $$\rho(z) = \rho_0[1 - (\alpha a - \beta b)(z - z_0)],$$

which expresses the dependence of density on local known or measurable seawater parameters.

It also follows that the water column will be statistically stable whenever

5) $\alpha a - \beta b \rangle 0$, which is commonly the case, except under exceptional conditions of strong vertical mixing or convection.

The potential energy (PE) per unit horizontal area for a column of water extending from depth z_0 up to level h will be:

6) $$PE(T,S) = \int_{z_0}^{z_0+h} \rho g(z - z_0)dz = \rho_0 g\left[\frac{1}{2}h^2 - \frac{1}{3}(\alpha a - \beta b)h^3\right],$$

where g is the acceleration due to gravity.

If this stable stratified water column is completely mixed in salinity and temperature, it can be shown that the new potential energy will be,

7) $$PE(\overline{T},\overline{S}) = \int_{z_0}^{z_0+h} \overline{\rho} g(z - z_0)dz = \rho_0 g\left[\frac{1}{2}h^2 - \frac{1}{4}(\alpha a - \beta b)h^3\right],$$

which obviously is larger than for the former stratified situation. Such mixing e.g. by wind supplies energy to the water column and increases its potential energy.

However, for water flowing inside a vertical tube of length h, heat can mix or be exchanged, but not salt. It can be shown (Golmen and Cushman-Roisin 1992) that in such a case the potential energy changes by,

8) $$\Delta PE = PE(\overline{T},S) - PE(T,S) = \frac{1}{12}\rho_0 g \alpha a h^3 .$$

When a is negative (cold surface water), this means that the potential energy actually has decreased, and the centre of gravity has been lowered. Such a decrease in energy may be transferred to kinetic energy, by sustaining a flow inside the tube. This explains in essence the working principle of the "diffusive pump". It has actually been shown in recent small-scale lab. experiments that under such controlled conditions the pump really works (see chapter 4).

In a real situation, e.g, in a fjord, the vertical flow in the tube will tend to erase the vertical gradients. If the pump shall work continuously, this effect must be counteracted by a steady horisontal inflow/outflow of water in both layers to maintain the gradients, which actually commonly occurs in fjords. Alternatively, for some applications, the pump might be allowed to drift and thus not depleting the energy at a fixed location.

2.3 Related principles and technologies

The working principle of the diffusive pump may have some similarities with other energy-generating or converting techniques. A few of these are briefly mentioned here, as it is anticipated that further studies and tests of the pump may benefit from experience gained in related fields of research.

2.3.1 OTEC

OTEC (Ocean Thermal Energy Conversion) is a form of energy generation that uses the heat of the surface water of tropical oceans to generate electricity for on-land facilities or for ship-mounted plants that produce fuels for other products (Avery and Wu, 1994). The clue is to exchange heat between the cold deepwater that is pumped from several hundred metres of depth and the warm surface water. The deepwater is used to condense vaporised working fluid, after the vapour has been run though a turbine or turbo generator.

In open-cycle OTEC plants the working fluid is water or water vapour, that is discharged after evaporation and condensing. Such plants may also be used to produce fresh water. Closed-cycle OTEC plants use a recycling fluid such as ammonia as working fluid. Most research efforts have been devoted to this OTEC type. The NEHLA research facility at Kona Island in Hawaii is renowned for its OTEC research. The OTEC/DOWA association in Taiwan promotes research on OTEC technologies which has experienced several setbacks in the past decades, but which is expected to gain more attention in the future as technical developments are progressing and the search for new energies will intensify.

2.3.2 Energy from salinity gradients (salinity energy)

When a solution of salt water is separated from a volume of freshwater by a semipermeable membrane, osmotic pressure is excerted on the membrane, and causing freshwater to flow across and into the saltwater which then may expand and increase its hydrostatic pressure. It has been estimated that the energy potential resulting from the osmotic contact between fresh water and saltwater can equal that of a waterfall, or of a hydroelectric dam 250 m high! Mixing 1 m^3 of freshwater with seawater would release 2.24 MW of energy (Charlier and Justus 1993).

The technology to extract such energy is still in its early stages, mainly due to lack of efficient membranes. The expectancy is that membranes can handle freshwater fluxes on the order of 10 l/m^2 hr (Thorsen 1996). In theory tremendous amounts of energy could be retrieved where rivers debauch into the ocean. Some research on this has also been performed in Norway (Thorsen 1996). The alternative principle of "reversed osmosis" is commonly applied to produce freshwater from seawater.

The heat of dilution between seawater and freshwater is about 0.5 °C. This heat is released when rivers mix with the seawater in the estuary. This heat could in principle be extracted and used for power generation etc.

2.3.3 Heat pumps

A heat pump is a device for transferring heat from a low temperature source to a high temperature region, by doing work. The working fluid is at one stage a vapour, which is compressed by a pump adiabatically. At the radiator the fluid is cooled by transferring heat to the space or device to be heated. Heat pumps of various designs are widely distributed and applied e.g. for heating of buildings or industrial plants. Related technologies are refrigeration and air conditioning. Many countries have launched their own 'Heat pump" research programmes. The international energy agency (IEA) has its own Heat Pump Programme, and Centre, for which the Netherlands is the operating agent (IEA 1996).

3. Seawater stratification and circulation

The *diffusive pump* may not work under any hydrographic condition, but most certainly during conditions where the ambient seawater is stratified (layered) in a certain manner like in sub-Arctic fjords in wintertime. Also the circulation pattern (currents) may work either pro or against the efficiency of the pump. Therefore we find it useful to give a brief review of the typical oceanographic conditions, especially those in fjords and coastal waters were the pump may have optimum working conditions.

3.1 Stratification

Oceanic and coastal waters are under most conditions stable stratified, i.e. light water always lies on top of more dense seawater. The density of seawater, as expressed in e.g. kg/m^3, is determined by the physical water properties temperature, salinity (salt content) and pressure. For seawater density increases with decreasing temperature and increasing salinity. Increasing pressure causes the water to be compressed, so in very deep water the in-situ density may be several tens of kg/m^3 higher than for water with corresponding temperature and salinity characteristics at surface pressure. However, for the scales in rather shallow water we are considering, the pressure effect on density may at first hand be ignored. Fig. 3.1. shows how the seawater density varies with temperature and salinity, at atmospheric pressure.

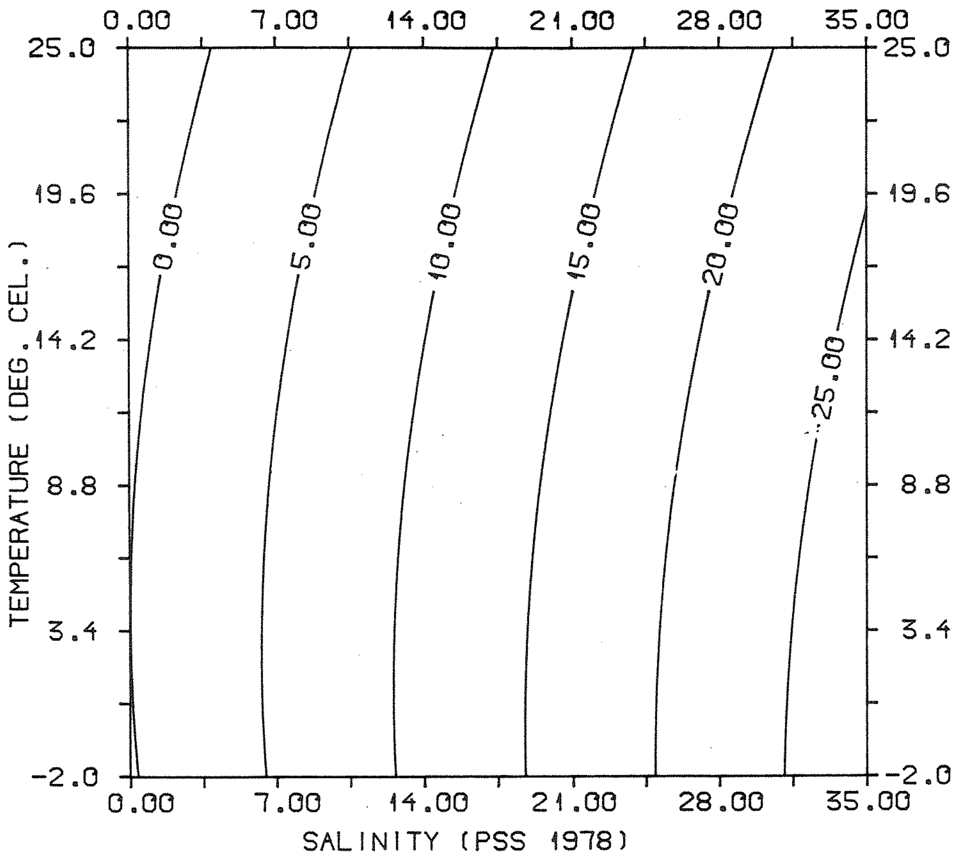

Fig. 3.1. A Temperature-Salinity diagram (T-S diagram) showing the dependence of the seawater density as function of salinity and temperature (°C) at 1 atm. pressure. The density values are sigma-t values (kg/m^3 - 1000). Oceanic water weights about 1025 kg/m^3.

The stratification can take on various forms and magnitudes. The simplest case will be a low salinity layer of brackish water lying on top of a nearly homogeneous saltier deep water. This situation is quite commonly found in fjords and coastal embayments which receive some freshwater runoff from rivers or streams. An example from a fjord is shown in Fig. 3.2.

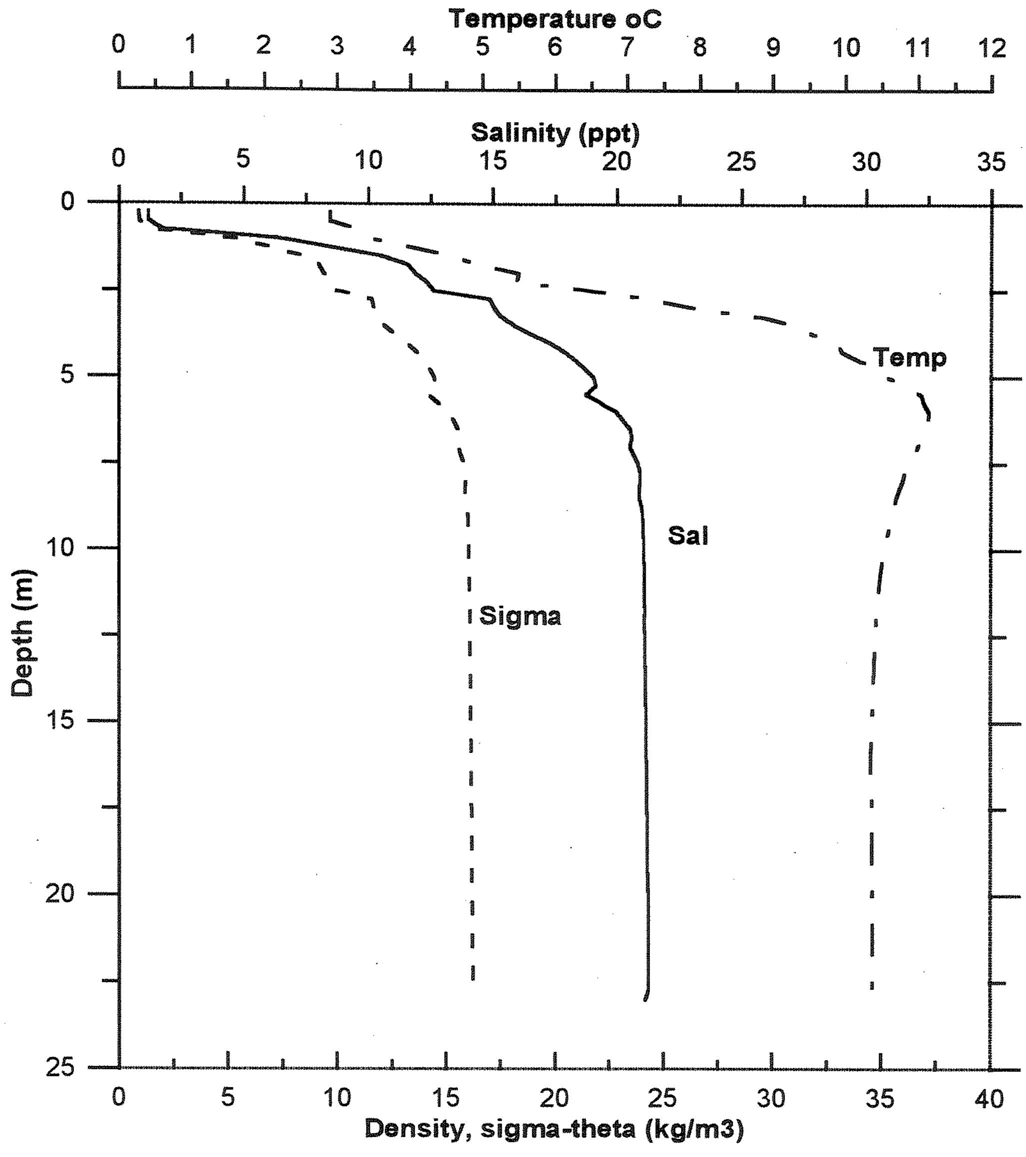

Fig. 3.2. Example of measured vertical distribution of salinity (Sal), temperature (Temp) and density (Sigma) in seawater. The profiles are from a small fjord in February, 1995 (from Golmen et al. 1995). This fjord has a very shallow sill, and the pycnocline is found between ca 2 m and 5 m depth. The top layer was cold (1-2 °C) and fresh (sal < 10 ppt). Underneath there was a layer with higher temperatures, with T_{max} of about 11 °C at 6 m depth. This fjord has permanent anoxic deep water. At the time of the observations the O_2/H_2S interface was found at 3.5 m depth. Sometimes it is found very near the surface, when odorous H_2S leaks to the air.

In the vicinity of the mouth or entrance of the fjord, a shallow region or sill is commonly found. This sill restricts the deep water circulation to intermittent or episodic events only, with long periods of stagnation in between.

Figs. 3.3 illustrates different hydrographic regimes that may exist inside a fjord. The layers above sill depth will be subject to relatively frequent renewal, which is driven partly by density variations and internal waves in the coastal water and partly due to freshwater runoff and tides.

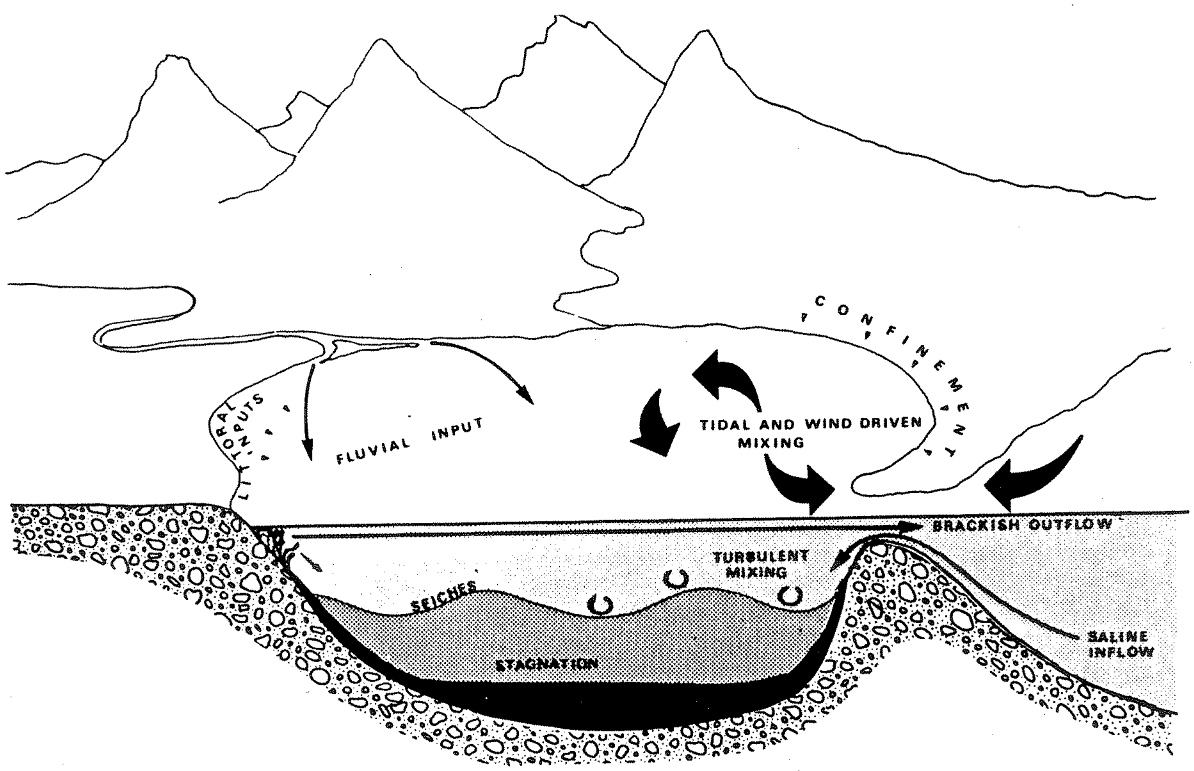

Figure 3.3. Schematic diagram of various environmental factors concerning fjords. From Pearson (1980).

A primary well defined pycnocline marks the division between the brackish surface layer and the intermediate water. Between the homogeneous deep water and the intermediate water a secondary pycnocline prevails throughout most of the year. At both these interfaces (pycnoclines) internal gravity waves may exist more or less permanently.

The deep water and sediment chemistry may vary according to the actual topography, the organic load and other factors (Aure and Stigebrandt 1989). Many sill fjords experience seasonal oxygen depletion in the deep water, sometimes leading to anoxia. Other fjords may have permanent anoxia in the deep strata. The profiles shown in Fig. 3.2 are from a fjord or meromictic lake which has anoxic deepwater. Fig. 3.4 shows a section of salinity along the 12 km long Bolstadfjord, Western Norway. The sill in this case is long and extremely shallow (1-2 m). The two major deep basins inside the sill suffers from anoxia, as was the case during the two surveys that are represented by Fig. 3.4. This fjord may be regarded as an 'outlier' with respect to the salinity distribution normally found in larger fjords, as the surface layer is very deep and has a very low salinity (usually 0-2 ppt in upper 20 metres).

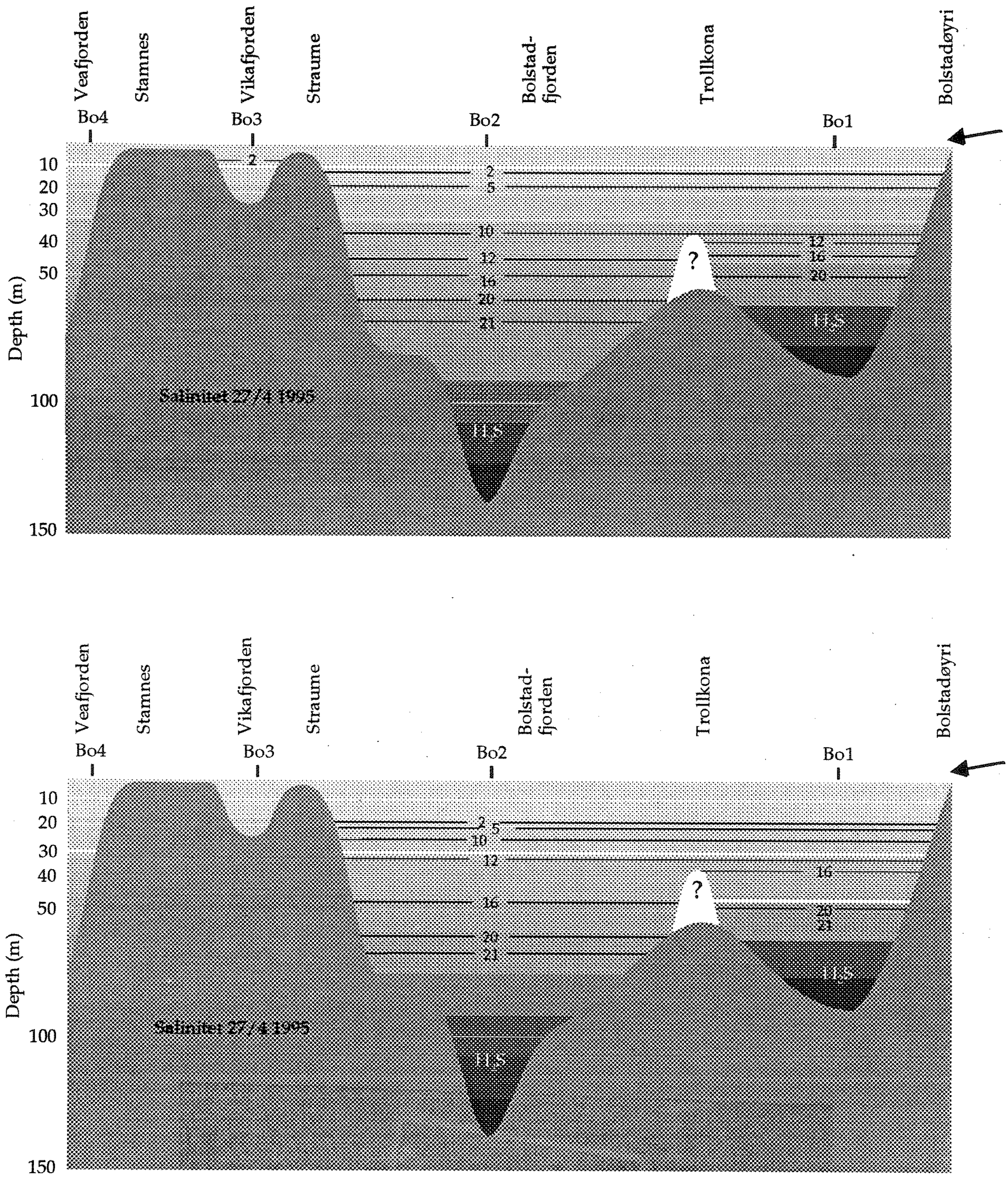

Figure 3.4. Vertical section along the Bolstadfjord, 1 June 1994 and 27 April 1995, showing isolines of salinity. The deep water had significant amounts of H_2S, with water samples showing values of up to 30 mg/l. The difference in deepwater characteristica in the two main basins indicates that the sill between them near Trollkona is at about 35 m deep (from Bjerknes et al. 1995).

Many of the fjords that are of interest in the present study have a deep sill which does not impose a serious restriction to water exchange as do shallow sills. The water quality in the basins of the deep fjords is expected to be satisfactory in terms of dissolved oxygen content. However, the lack of regular monitoring of Norwegian fjords in general may disguise the fact that several deep fjords actually may exhibit seasonal oxygen depletion.

During periods of stagnation slow vertical diffusion cause a gradual reduction in sea water density, thus preconditioning this water to renewal by denser water from outside. A diffusion-driven reduction of less than 1 sigma-t unit may be sufficient for a renewal to take place. Deep water renewal is expected to occur in late winter or spring. Prior to this, dense coastal deep water is upwelled at the coast and then circulated across the sill and into the deep basin. The actual density of the inflowing water and the basin water will determine if the new water flows along the bottom, or interleaves in the water column. Statistical approaches may be taken in order to compute the renewal time, based on long-term data on sea water density in the coastal water (Stigebrandt 1992).

Ice formation is another physical phenomena occurring regularly in sub-Arctic fjords in the wintertime, and that is tightly connected to the hydrographic conditions. The existence of a thin, brackish surface layer tends to enhance ice formation. Open fjords exposed to wind and waves are less susceptible to ice formation.

3.2 Water circulation

Along with the stratification, certain water circulation patterns will exist in the fjords and in coastal waters. Such circulation will be driven by one or more factors or forces which are time-varying:

- Tides
- Wind
- Horizontal seawater density gradients
- Fresh water input
- Cooling/heating at the sea surface
- Internal waves and mixing

Fjords and embayments with some river drainage usually will have a net outward (seaward) flow in the top, brackish layer, and a reverse, inward flow beneath, extending to ca. mid depth or to the depth of the sill at the mouth or entrance. Water speed can exceed 50 cm/s in the top layer. Usually currents are weaker at depth, but speeds of 0.2-0.5 cm/s may be expected in many places.

Currents will not be steady, but may vary in time according to the above list of governing forces. The tide is the most regular and predictable factor. The effects of meteorological factors can be studied by comparison between simultaneously collected meteorological data and oceanographic data. Internal waves may also be a frequent and perhaps disturbing feature, and a brief description of such phenomena is given below.

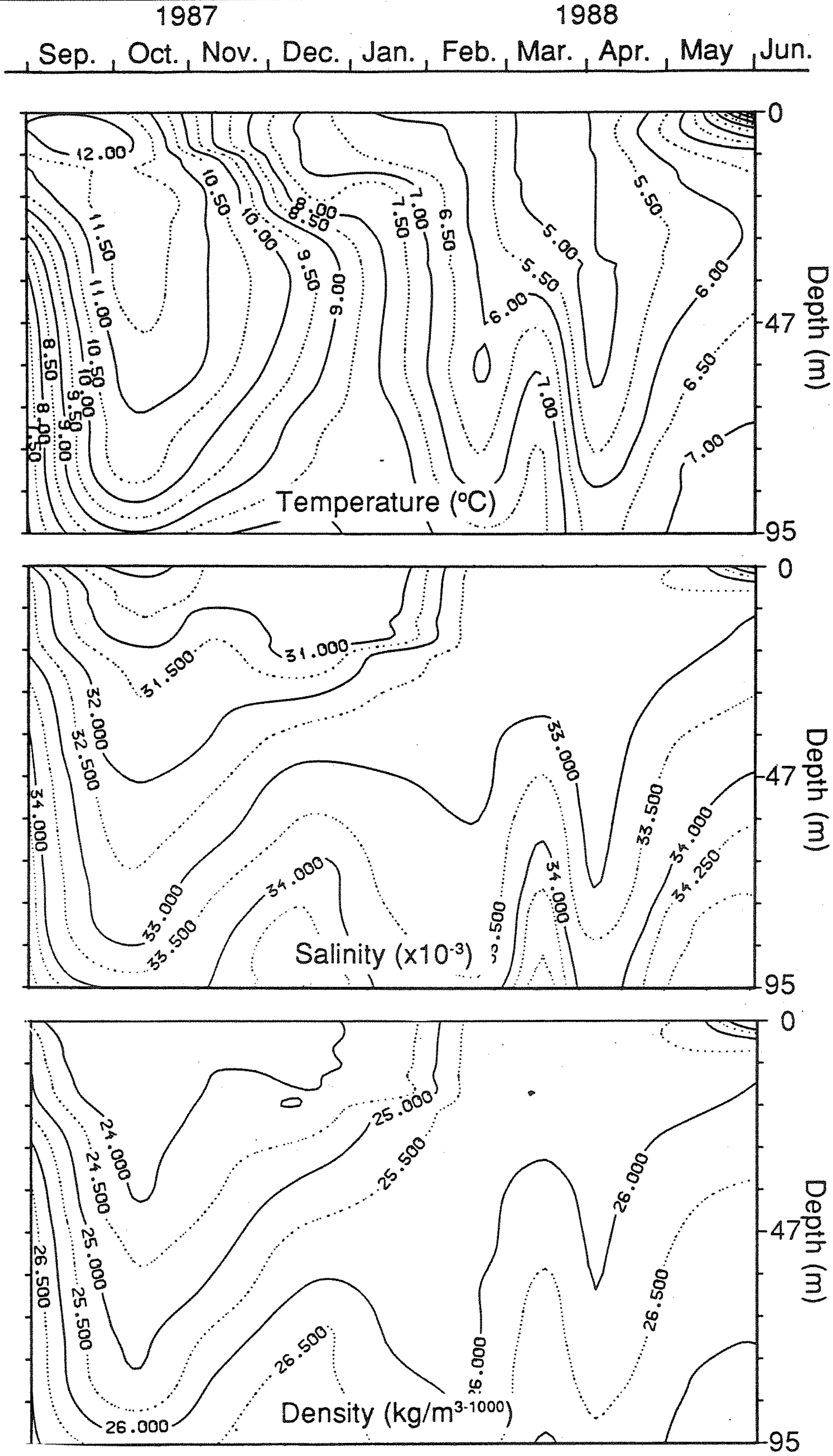

Fig. 3.5. Isolines of temperature, salinity and sigma-t versus time and depth, Sept. 1987-May 1988, as observed by NIVA in a fjord on the west coast of Norway. The sill depth is about 20 metres, and the fjord is only moderately stratified due to frequent exchange with the coastal water.

The current pattern and exchange with external waters will determine the variability in the water masses inside the fjord. An example from a fjord close to the coast is shown in Fig. 3.5.

A diffusive pump placed in the shallow waters of a fjord will act to redistribute some heat and salt within the fjord. The extent of this will mainly depend on the size of the fjord and the capacity of the pump. With a cold surface layer, the pump may tend to increase the temperature in water surrounding the radiators while warmer water is circulating inside. If this heat is not carried away, the efficiency of the pump will decrease due to less efficient cooling. Therefore also the horizontal circulation pattern in the fjord must be considered in a detailed site-specific feasibility study.

3.3 Internal waves

Internal waves manifest themselves as time-varying vertical oscillations of the iso-haline or iso-thermal surfaces. At anyone location in a fjord this can be measured as variation in depth of certain iso-halines or isotherms, sometimes several tens of meters in amplitude. Fluctuating currents will be associated with these variations. Certain precautions may have to be considered if placing a diffusive pump unit in a location with enhanced internal wave activity. As the pychnocline will travel up and down, the optimum working depth of the pump may also have to be varied according to this by some means. The currents induced by the internal waves may on he other hand act to enhance the efficiency of the pump due to extra flushing of the radiator part.

Tidal flow over topographic features such as an entrance sill to a fjord can produce internal waves. Sandstrom (1991) interestingly gives the historical record of modern research in this field. Tidal flow over a sill may generate internal tides, but can also produce high frequency internal wave trains and vertical instabilities downstream of the sill (Farmer and Smith, 1980). Reflection of internal waves from the sloping bottom or the fjord surface may cause a change of vertical phase propagation, and interaction between several internal wave modes. Possible breaking and dissipation of internal waves at the head of the fjord adds to the already complex nature of internal waves.

Internal waves in fjords play an important role in the vertical transport of heat and matter such as salt, oxygen and nutrients in an otherwise stagnant basin water. Vertical transport of heat and salt is important for the diffusive conditioning of the basin water to the often occurring annual or semi-annual dense water inflow and subsequent deep water renewal. The vertical transport of oxygen and nutrients may be crucial to the maintaining of satisfactory water quality and a diversified ecological system in the deep water.

Because the complex nature and mode interaction of internal waves, a clear and regular signal often is masked in observations. Waves may often be seen as trancient phenomena which is triggered by e.g. meteorological phenomena. The signature of internal waves depends on the vertical density distribution (stratification). As the stratification of fjords often shows a strong seasonality, the strength of the internal wave signal also will be seasonal.

4. Discussion of some designs and applications

A pump devise as described in this report may take on various forms and shapes. The simplest device may consist of a horizontal radiator surface, with several tubes running in parallel, and vertical tubes stretching vertically to either a fixed depth, or a variable depth, as depicted in Fig. 4.1.

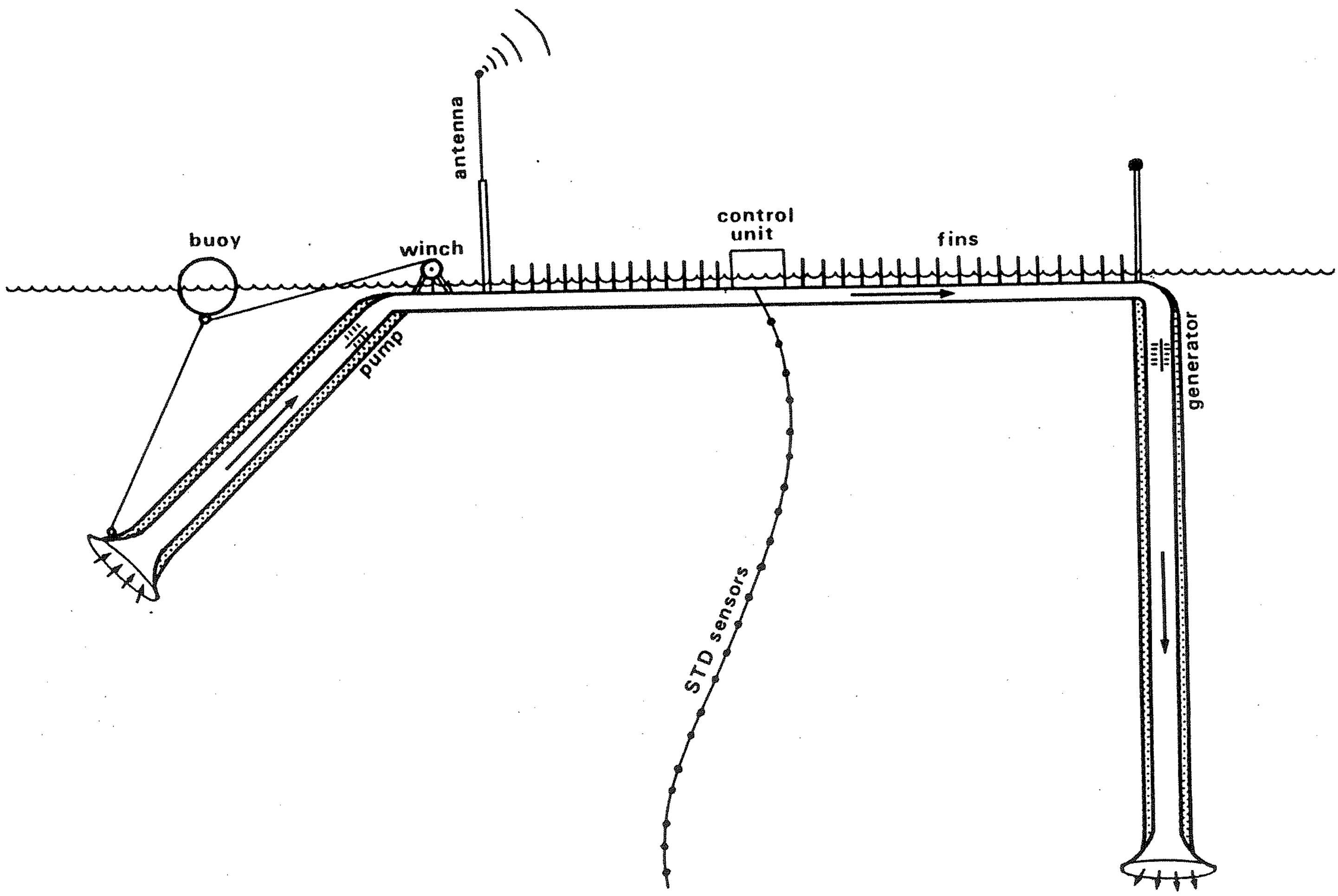

Fig. 4.1. Schematic of a "diffusive pump", which consists of a horizontal radiator-surface and vertical tubes. In this case, the depth of the water intake is varied automatically according to the actual state of the surrounding hydrographic conditions. Seawater characteristica are continuously monitored by sensors, and a central control unit adjusts the water intake to maximise flow.

4.1 Optimising efficiency

Probably significant achievements in efficiency and power output can be obtained with optimum design and location of the pump. The first step should be to design and run a laboratory tank tests where both the shape of the pump may be varied, as well as the ambient stratification. Initial experiments have already been performed in the USA. The next step will be to run tests with a prototype, in a selected fjord.

4.1.1 Site evaluation:

It may be that the fjord which has the optimum conditions for power output may not have an explicit local demand for power, heat, water quality improvement etc. So when selecting sites for future installations, local demand must be assessed beforehand. Anyway, selection of location (site) for a prototype installation may not be linked to local demand, and can be envisaged being performed according to criteria such as:

a) Stratification of salinity and temperature: The average conditions should be assessed beforehand by a monitoring programme in the selected fjord that extends minimum 1-2 years. A local observer may collect data with automatic sensors and instruments that are lowered into the water (STD or CTD probes), and that stores data internally. Such sampling can be performed e.g. once every 2nd week, and with a local observer, the cost of such a programme will be small.

b) Water circulation: For the detailed design computations on cooling/heating efficiency and on mechanical strength, it will be necessary to apply data on water currents. Such measurements will also give background data to compute the theoretical capacity of the fjord, i.e. power extraction as a function of local water replenishment. Performing such measurements may require more resources than measurements of stratification (hydrography). New types of instruments such as Doppler profiling current meters (ADCPs) that measure currents from the surface or bottom simultaneously at many different depths can be applied, e.g. from a small boat in steady motion. By surveying the fjord in repeated transects at different seasons and meteorological conditions, a good impression of the currents in the upper layers can be obtained.

c) Local infrastructure: The prototype should preferably be installed at a site with some existing infrastructure. An aquaculture farm might be suitable for this, as local staff will be available any time for inspection. Precautions must be made, so that local contamination does not affect the tests.

d) Water quality: This parameter may be important in terms of future operation of pump units for water quality improvement. For running the prototype, this is probably of less importance, but strongly polluted areas for the tests should be avoided. Also, marine growth can be stimulated in sites near sewage outfalls and possibly also near aquaculture farms, so this aspect should be evaluated beforehand, when selecting the site.

4.1.2 Prototype design and operation

The work to design the prototype may be as:

a) Optimising design: Based on detailed information about the ambient conditions such as currents and seawater temperature (incl. temporal variation), design criteria must be established, and drawings made. Existing software programs for fluid flow in pipes etc. (*MATLAB, Fluent*),can be utilised for the computations, and for subsequent computer simulations. This part also includes selection of best available material in terms of heat conduction, heat insulation, mechanical resistance and strength. It is envisaged that for the first prototype, the automatic control unit with sensors etc. is not installed. In stead, any variation in design like tube length and operating depth of the prototype unit will be done manually. This also applies to collection of essential operating efficiency parameters such as flow inside the tubes.

b) Detailed cost assessment: At some stage, probably after the above activities have been performed, or at least are in progress, a detailed cost plan for constructing, installing and monitoring of the prototype must be performed. A draft cost plan should be available prior to start-up of the project (i.e. also before the start of the ambient monitoring programme).Connections should be made to organisations such as the international Ocean Floating Platform Alliance (1st summit meeting to be held on Dec. 3-5, 1998) and the OTEC/DOWA Association.

c) Market analysis: Following the prototype tests, a market analysis may be performed. This will also link to other project modules. If this analysis turns out with encouraging results, a program should be set up for further technical developments and eventual manufacturing of diffusive pump units.

4.2 Some suggested applications

4.2.1 Power generation

A device with a 10 x 10 m radiator surface, placed in a Norwegian fjord under 'normal' winter conditions, can produce at least 1 kW of power according to previous estimates (Golmen and Cushman-Roisin 1992). This may even be a moderate estimate, as significant achievements can be obtained with optimum design and location. With an array of units, several kWs of power may be generated in wintertime within a fjord. This coincides with the peak demand for electricity in Norway, and may thus be interesting for some applications (e.g. heating) despite the moderate supply. Prototype tests are needed to assess this in more detail.

4.2.2 Aquaculture

Aquaculture farms depend on adequate water quality inside and around the net cages. A self-sustained diffusive pump might represent a good way to meet the water quality criteria for fish, by continually bringing clean water up, and polluted water down. Also, if electric power is generated in addition, this can be consumed by specific equipment on the fish farm.

The pump may also act to reduce or break down the pycnocline, and simultaneously bring nutrient-rich water upward to the shallow layers. This may be an interesting application e.g. for mussel/oyster farming, that is a growing business in Norway. The growth of the mussels depends on a steady supply of nutrient-rich water.

4.2.3 Fjord restoration

Many fjords and small landlocked bays suffer from reduced water quality, either seasonally or permanent. The diffusive pump would offer a sophisticated, but yet simple way of stimulating internal mixing and the vertical water exchange, and thus improve the water quality. The pump would run free of cost of operating pumps, contrary to existing methods for restoration.

4.2.4 Local heating

As the expected period of maximum power output from a diffusive pump may coincide with extraordinary cold air temperatures, supplying the electricity or energy locally for e.g. heating may be one way of using the energy. The pump might supply electricity to resistance cables to melt snow/ice on critical roadstretches.

Geothermal heat stored during summertime in shallow earth layers is already used to melt ice on roads in the wintertime, by a combination of a heat exchanger, a heat pump and heating pipes buried under the road. The Gaia system of Ninone City in Japan demonstrated an energy reduction of 84%, compared with using regular electric cables (CADDET Technical Brochure No. 76, 1998). Developments of the diffusive pump in combination e.g. with a heat pump to build a similar system should be investigated.

4.2.5 Maintaining ice-free conditions

Many fjords are ice-covered in wintertime. This restricts boat traffic, and usually is regarded as a negative environmental factor. By applying an inverted-'U-shaped' diffusive pump, with the radiator placed in the cold surface layer, the warm water being pumped through may reduce the cooling of the surface water, and thus retard or eliminate ice freezing.

4.2.6 Heat pumps

The simple principle for the diffusive pump as described here, does not involve any closed cycles and condensing/vaporisation such as in heat pump systems. There may be applications, however, where a heat pump can increase its efficiency by working in combination with the diffusive pump. The radiator unit of the diffusive pump may e.g. be connected to the heat absorber or heat exchanger (depending of pump design and operation) of the heat pump, thus enhancing the efficiency of both systems.

4.2.7 Freshwater applications

The pump concept has been described from a 'saltwater' point of view. However, the pump should also work in freshwater lakes, during periods where a significant thermocline exists. Applications in lakes may be similar to those described for a fjord.

4.3 Biofouling

Like on any marine construction, biofouling may pose a problem to the pump. Settlement and growth outside and inside of the tube walls will reduce the over-all efficiency by slowing down the flow inside and around the pump and by reducing the thermal conduction through the walls and the advection of heat around the structure. Also heavy contamination on the outside may pose a buoyancy problem to a floating or submersed pump structure, and it will enhance the mechanical strain due to the drag from currents and waves. Thus such growth at any rate should be avoided or reduced to a minimum.

For OTEC plants the effect of biofouling on heat conduction was determined to be of minor importance (Avery and Wu 1994, p. 36). The pump described in this report will mostly operate in the season of low growth and primary production in the sea, so the contamination problem may not become serious provided the pumps will be stored out of water during the off-season. But anyway the contamination issue will have to be addressed in this report and considered when constructing the pump devices.

Algae require light for their growth, while other marine organisms can exist without light. That means that the upward facing parts of the pump structure will be most susceptible to growth by algae, while animals can settle also inside the pipes. Thus, the deeper the structure is, the less algae contamination can be expected. This also holds true for many animal species, but some can be attached even at large depth.

Salinity tolerance affects species composition of algae. Some species have a high tolerance, e.g. 4-34 ppt for *Fucus vesiculosus* (Rueness 1977), while others will have a narrower tolerance. Several animal species can tolerate the low-salinity environment in fjords (Campbell 1977).

The common mussel (*Mytilus edulis*) and acorn barnacle (*Balanus balanoides*) can form dense communities to depths of about 20-25 m in Norwegian fjords (Kvalvågnes et al. 1974). Hydroids are also able to form dense colonies on smooth surfaces such as tube walls, and thus create significant flow friction if allowed to settle. Most of these dwell in shallow water. Fan worms with calcareous tubes are common contaminators on heat exhangers, cooling water intakes etc.

The conventional OTEC plants draw water from very large depths (800-1,000 m), and the the problem of contamination have been determined to be practically manageable (Avery and Wy 1994). The situation may be different for a structure in shallow waters.

There are means to avoid marine contamination, such as:

- Priming the exposed surfaces with biofouling paint
- Temporary flushing the system with low concentration of chlorine or hypochlorite
- UV radiation
- Mechanical cleaning.

From an environmental point of view, use of primers or chlorine should be avoided as much as possible. Biofouling films may also reduce the heat conduction. Mechanical cleaning may be necessary from time to time to get rid of some species, like barnacles and calcareous tube worms. Smooth surfaces will be less suceptible to contamination than rough surfaces, so material type should be carefully selected.

As previously described the pump will have optimum working conditons in the cool season, i.e. from October to April. This is the season of lowest contamination risk, so the problem caused by marine growth may thus not be serious. However, the risk should be assessed for every new pump device, and caution should be excercised when selecting material, shape of the tube and depth of operation.

4.4 Results from a recent lab. experiment

In early 1998 a small-scale laboratory test of the diffusive pump was performed by prof. B. Cushman-Roisin and one of his students at Dartmouth College in New Hapshire, USA. The results were encouraging. Even for moderate temperature differences in the tank (12 °C), the flow went by itself, even without any need for priming (B. Cushman-Roisin, pers. comm). Fig. 4.2 shows some photograps of this tank experiment, where the dye visualises the flow. *These first experiments show that the pump works, under controlled laboratory conditions.* New experiments are being planned at Dartmouth college.

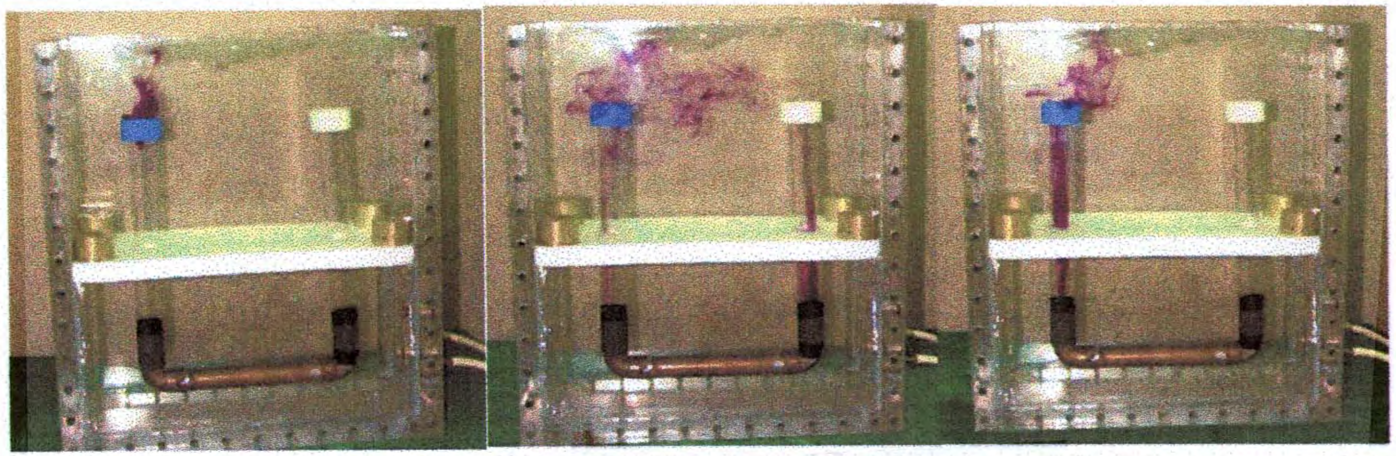

Fig. 4.2. Photographs of the recent tank experiments on the diffusive pump that was performed at Dartmouth College in New Hampshire, USAby prof. B. Cushman-Roisin. The flow started by itself, without any initial priming. The dye marks the outflowing water in the left tube. Stratificaton was maintained by the white insulating styrofoam board. The top layer was kept cool by adding ice, and the lower layer had a continuous throughflow of warm water.

5. Concluding remarks and recommendations

This preliminary feasibility study describes the basic working principle of the diffusive pump, and a few applications have been suggested. The concept as described, provides a means of exploiting new energy, which in fact is solar energy from the summer season that is stored in the deeper layers of the fjords throughout the winter.

Provided that industrial companies or other energy-related institutions may become interested in further development of the pump concept, a next phase with laboratory tank tests should be followed by construction and testing of a prototype (size scale on the order of 10 m) in a fjord. The report describes briefly how this could proceed.

Both governments and large companies are putting more efforts into investigating alternative energies to oil, coal, hydropower and nuclear power. This is a process that is driven by factors such as the global warming, and by different NGO stakeholders such as Greenpeace. Emphasis is placed on solar energy exploitation, which the diffusive pump can be said to represent a form of. So there may be a potential for funding the prototype tests and further developments.

One of the described goals that the diffusive pump might achieve, is improving environmental factors such as water quality in fjords. However, the change in stratification, and redistribution of heat in the water column that a pump of some size may effect, may theoretically have some negative impact on local marine biota or on local climatic conditions. These environmental aspects should be addressed and assessed before installing a pump. The winter season will probably be the optimum period for pump operation. This coincides with low biological productivity in the water, so effect on biota may be of less importance. Running the pump e.g. to maintain ice-free conditions may cause more fog under certain meteorological conditions.

If the flow of the pump is significant as compared to the normal horizontal water fluxes of the fjord, the pump may theoretically act to change the circulation pattern. Such changes should be assessed by running a hydrodynamic model incorporating simulations of the vertical flow and heat-redistribution made by the pump.

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