Cooling Coral Habitats by Convection

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Abstract. The rise of ocean temperature and the acidification of seawater caused by global warming have dealt a near catastrophic blow to corals living in shallow waters. The massive coral deaths, which have proven to be an impact of fishing, tourism and the marine ecological system, will continuously deteriorate to a stage that impairs human environment, which makes it badly-needed to reach the resolutions. Based on previous studies on the effects of current mixing in the ocean, this project mainly utilizes convective heat transfer theories: Cooling surface water by ejecting cooling air, and circulating cooling bottom water by forced convection. It attempts to imitate and amplify natural oceanic activities to reduce the disturbance. Meanwhile, some substances are sprayed to promote the growth of phytoplankton for the acidity reduction of seawater. Additionally, setting specific constrains and preconditions according to coral habitats (continental shelf) may allow this design to be more suitable and effective. Afterwards, the project is simulated and tested on the software Workbench Fluent. Results show that the device is capable of refrigeration, and theoretically meets the design requirement of cooling more than 2℃. The temperature field of the convective process is also clearly depicted, which indicates that the cooling mechanism of the convective circulation can be technically realized.

1. Introduction

Global warming during the past two centuries has caused severe influence on ecological systems including marine system. Glacier ablation in polar areas has resulted in not only the sea level rise and island inundation, but also the more frequent extreme disasters that disturb the regular life activities\cite{1}. Meanwhile, anomalous high ocean temperature will force corals to discharge symbiotic algae, resulting in coral calcification and color whitening, which is acknowledged as “death”. Temperature increase of 0.13℃ in global oceanic shallow water has destroyed over 67% coral reefs in Australia, and as calculated, coral reefs will decrease by 70%~90% with global warming of 1.5 ℃, and disappear at 2℃ (>99%)\cite{2}. Additionally, global ocean has absorbed approximately 20%~30% of the human-generated carbon dioxide emissions, causing its PH declined 0.1 degree\cite{1}. This is also the accomplice of coral death. Severe coral mortality would be a huge strike to the tourism and the fishing industry in those ocean-relied regions. As early as 1994, the annual tourism revenue of the Great Barrier Reef had reached A$682 million Australian dollars. According to the report issued by the Economic Research Institute in 2013, the annual consumption efficiency of the Great Barrier Reef was about 5.02 billion. In 1990, the annual income of tourism in the Caribbean reached 8.9 billion US dollars\cite{3}. About 10% of global fishery production comes from coral reef areas. Nearly all corals in Kenya suffered mortality rates of more than 40% in 1998, which led to a 21% decline in the per capita catch of aquatic products in that year\cite{4}. Scholars explained it through three reasons: the proliferation of certain harmful algae, the decline in shelters for fish from predators, and the sharp decline in food provided by corals, which were all caused...
by coral deaths. Coral reefs may have a greater significance for the ecological system. Coral reefs play a crucial role in global carbon cycle and calcium balance\cite{5}. Healthy corals act like a natural breakwaters in protecting fragile coastlines from wave erosion, and reduce the risk of marine disasters for coastal residents\cite{6}. Corals may promote the growth of mangroves and sea grass beds, and play a key role in maintaining marine biodiversity\cite{7}. Although coral reefs account for only 0.1%-0.5% of the world's ocean area, they serve as the environment on which 30% of marine lives depend\cite{8}, and are compared to the "tropical rain forest" in the ocean. If the coral loss deteriorates to an irreversible stage, the stability of the delicate ecosystem would be tremendously damaged, and shortly afterwards the turbulence will spread to terrestrial ecosystem\cite{6}.

Out of concern for these grave consequences, this project is promoted to alleviate this disaster.

2. Materials and methods

2.1. Inspiring precedents

The previous trials for the Earth cooling were inclined to create a layer of artificial “mirror”, by which the reflectivity may increase while the penetration may decrease (the sum of these two percentages and absorptivity part are equal to 1). Therefore, the heat crossing the atmosphere then reaching the Earth surface could be limited. Professor Roger Angel of the University of Arizona tried to utilize trillions of micro satellites orbiting the Earth and creating a sunshade. Some other engineers counted on sulphur or hydrogen sulphide aerosols as a duplication of volcanic ash, and some preferred more snow to be exposed to reflect sunshine. However, these kinds of projects generally called geo-engineering projects are too large to be reliably controlled. Dr Phil Rasch of the US-based Pacific Northwest National Laboratory once predicted their potential negative effects on polar areas and global rainfall. Meanwhile, the considerable investment and cutting-edge technology also deter them from implementation.

Consequently, later researches resorted to local and targeted programs, beginning with the studies on natural phenomena that may cause temperature drop. Research has revealed that in equatorial sea area, mixing between upper water and bottom water did have effect on the whole water temperature\cite{9}. The whole temperature rose by 2 Kelvin when lower water was heated up by hot surface water through mixing in summer. Similarly, in winter, sunshine provided too little heat for the upper layer which would be cooled when mixed with lower layer. In the study of Typhoon Sinlaku in 2008\cite{10}, scholars drew a conclusion that the cooling of seawater below 30m is mainly elicited by vertical convection or upwelling. Additionally, they acclaimed that: typhoons, with stir and vortex, may enhance the vertical turbulent mixing of seawater, thus allowing the seawater in the lower water to reach the surface layer more easily and frequently.

As for another problem that endangers corals -- CO$_2$, attention has always been paid on the photosynthesis of plants and phytoplankton, which consumes the CO$_2$. Apart from carbohydrates and oxygen, phytoplankton also release a dimethyl sulfide into the atmosphere to form sulfate aerosols, a substance that may both directly reflect sunlight and increase cloudiness to enhance reflectivity. This ability of phytoplankton inspired a geo-engineering approach similar to fertilizing crops: stimulating phytoplankton growth by large-scale dissemination of molysite or dimethyl sulfide and other supplementary nutrients, thereby aggrandizing dimethyl sulfide emissions and achieving cooling objective\cite{11}.

These precedent efforts inspire the design demonstrated in these issues.

2.2. Design

The target is set on rescuing corals living in shallow ocean, primarily because coral is rendered as one of the most endangered species, and they provide biological surroundings for other marine creatures. Besides, the temperature of their habitats is technically easy to measure, and their death is facially obvious (their color will change into white) which may lucidly demonstrate the acceleration or deceleration of their mortality rate.

The main task of this project is to create a cycle of convective heat transfer propelled by jetting cold
air. Its prototype is the bottom seawater upwelling caused by the confluence of ocean currents, which naturally happens during fishing season. Compared with the precedent projects which were designed largely involving artificial devices, a natural phenomenon may have much less negative byproduct. Despite the general fundamental theories, the specific type of objective, the habitat of coral, i.e., continental shelf, makes it necessary to decide several special and precise constraints: ① First, the shallow seawater covers a large area instead of a few square meters, which raises the concerns about the rational layout of the device, and financial problems about construction and later management. ② Second, because of the mild temperature fall (0.13°C), surface water merely needs to be cooled to the extent that coral can live. The magnitude of cooling does not need to be dramatic (1°C–2°C), which is tantamount to the minor difference between the temperature of refrigerant and of the environment. ③ Third, as a venerable ecosystem, the ocean is not able to bear a barbarous or intense operation. One of the appropriate ways is to replicate the normal oceanic mechanism while equipping with desired function.

The illustration by images is divided into parts: the vertical section elucidates the mechanism of this project, for the convective circulation it sparked is working on the vertical plane. The top view reveals the overall layout, which is arranged to ensure the integrity of convection and improve the efficiency of heat transfer from the engineering practice point of view.

Figure 1. Vertical section and mechanism

Figure 1 shows the vertical section of the project and illustrates its mechanism.

The whole convective cooling cycle is composed of three phases. Firstly, both main and branch pipes are situated in surface seawater and supported by pillars. A row of holes on both sides of the branch pipe eject cold air, rapidly cooling the surface sea water, while pushing forward the water contacted. Therefore, the shallow seawater is driven to form horizontal flows because of the frontal water thrust and friction caused by water viscosity, which is the first phase of the convection cycle (classified as forced convection). Thereafter, the kinetic energy of surface cold water will decrease gradually along the course. When the velocity declines to a certain degree, cold water will naturally settle down because its density is greater than that of hot water below. They will mix or replace the bottom hot water, or cool it by heat conduction, reducing the whole temperature, which is the second phase (classified as natural convection). Finally, because the surface water near the branches is pushed away, the bottom hot water will be sucked up due to the pressure difference. They will also be cooled and pushed forward by ensuing cold air coming out of the branches, so that the circulation continues.

Along with the cold air, branches also eject molysite or dimethyl sulfide, promoting the thrive of phytoplankton.

Figure 2. Top view
Figure 2 shows the top view of the overall layout. The two branches (branch 1 and branch 2) of I main pipe are not adjacent to each other, but separated by a distance that equals to the length of a branch (branch 2') of II main pipe. The main consideration is that the two branches of the same main pipe eject cold air in two opposite directions, which may cause a frontal collision of the flow in opposite direction under water, and may lose certain part of their kinetic energy. Potentially, the hot seawater in the lower layer cannot be driven upward, and the circulation cannot be further completed.

When branches of the same main pipe are separated, i.e., branches of two different main pipes are arrayed alternatively, flows leaving from the farthest terminal of two opposite branches are indirectly against each other. Shear force generated by this dislocation will lead to whirlpools, which have the ability to suck cold air deeper into the sea water and enhance the heat transfer effect and efficiency.

The timing of utilizing this installation may also reinforce its availability. If it runs in the evening, the air temperature is low, requiring less power (electricity) to cool the working substance. Besides, when there is a residential electricity trough at night, the load of cooling machine may serve as supplementary use, striking a load balance and easing the pressure of allocating peak and valley power generation. If its working period is set in summer when the sea is warmed up more significantly, currents converge and fishing season occur spontaneously. Therefore, the effect of mixing seawater on the ecological environment will be less intrusive.

Figure 3 shows the sea surface temperature. According to the NOAA observation data shown in the figure, sea surface temperature (SST) near the equator is approximately at 30°C (86°F) [12]. Corals live in waters less than 20 meters deep, which means the temperature of surface and bottom seawater is almost the same due to the good penetration of solar radiation.

Based on symmetry in layout, the simplified model divides the overall layout into independent and functionally identical units along the vertical and horizontal symmetrical axes. (top view is shown in Figure 4.)

3. Simulation with Fluent

3.1. Model building
The initial temperature of the whole control volume is set at 30°C. According to the NOAA observation data shown in the figure, sea surface temperature (SST) near the equator is approximately at 30°C (86°F) [12]. Corals live in waters less than 20 meters deep, which means the temperature of surface and bottom seawater is almost the same due to the good penetration of solar radiation.

Based on symmetry in layout, the simplified model divides the overall layout into independent and functionally identical units along the vertical and horizontal symmetrical axes. (top view is shown in Figure 4.)
Because of the simplification, the boundary conditions of the six surfaces of the control body will be: initial temperature $T_0 = 30^\circ$C; heat flux $q_0 = 0$. (Symmetry planes)

This simplification will not affect the evaluation of the effectiveness of the device, but also abridge the modeling and calculation processes.

From the point of view of engineering practice, the length of branch pipe is set to 5m. Meanwhile, the maximum distance that the ejected cold air pushes the seawater to reach is also controlled to be slightly greater than 5 meters (controlled by the speed of the jet). In this way, the opposite cold flows can be guaranteed to contact without fluctuating the boundary. Because of the symmetry, the length and width of the control body are 10 meters, and the height is 20 meters due to the livable water depth of corals. The whole control unit model for simulation and its ideal cyclic process is shown in figure 5.

The temperature of the ejected cold air streams (cold source) is set at 25°C. Considering that the application of gas-liquid two-phase flow simulation will cause turbulence, even no obvious phenomenon at some point, in Fluent simulation, the meteorological data are replaced by the corresponding kinetic energy and temperature of sea water for more intuitive analysis. After attempts, the speed of cold air ejection required for a 5-meter journey of surface water is ensured to be 5 m/s, and the speed of the corresponding cold water jet is 1 m/s calculated by Fluent automatically. What worth noting is that Fluent only display the temperature field of the water body itself excluding the cold source, therefore, the outlet of the cold source is not the lowest temperature region in the temperature field. On the contrary, the temperature decreases continuously along the direction of the jet velocity.

3.2. Results
Figure 6-1 Velocity field

Figure 6-2 Temperature field

Figure 6-3 Temperature field (another side)

Figure 6-1, Figure 6-2 and Figure 6-3 show the effect of the velocity and temperature fields of the project simulated by Fluent.

The simulation testifies the theoretical and technical success of the design. As can be seen from the figures, the temperature of the whole control body has dropped from the initial 30 degrees (red) to approximately 27.5 degrees (green). This change proves that the whole water volume has been cooled down, and the device meets the primary design requirement: the range of temperature drop (2°C). In addition, the cooling subsidence side (green) and the warm suction side (yellow and orange) of the
The convection cycle can also be clearly distinguished from the diagram, which shows that the convection cycles are highly concentrated and complete without being disorganized. Although, results still show some design-related flaws. For example, from the figure 6-1 of the velocity field, it can be seen that the velocities of the opposite upper water flows do not deflect when they pass by, and the nearby water is not driven to increase its speed. It manifests that the desired shear force and vortex are not visibly formed. This may be due to the low velocity of cold superficial water flows. The inertia force it gives to the water between the opposite flows is not able to exceed the inherent viscous force, so the interjacent water can not be agitated.

Afterwards, what needs to be reminded is the necessity of field experiment in the sea to verify the conclusion.

4. Conclusions
Simulation with computer proves that theoretically the device has an evident cooling effect, and the requirement of cooling 2°C can be met by setting parameters pertaining to the situation. Moreover, the convection cycle design has also been proved to be available, and can be technically realized.

Finally, this project has other drawbacks that are exposed at the time prior to simulation. First of all, it could be a technical crux to transport two phases of substance: cold air as gas and molysite or dimethyl sulfide as solid powder. Secondly, a slew of mainstays and grid largely in the water may aggravate the difficulty of construction. Third, the abnormal prosperity of phytoplankton might diminish the global precipitation, which may not only exacerbate the water shortage in some regions, but also disturb the distribution and regulations of global rivers[13]. Last but not least, variables such as the heat conduction through the air above, and the seasonal solar radiation are left out to study convective heat transfer separately.

Because the project has not been put into practical application, these factors should be incorporated into future research.

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