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Analysis of a subsea cooling system utilizing CFD

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Abstract: This research primarily investigates the computational fluid dynamics (CFD) analysis of a shell and tube heat exchanger designed for cooling the hydraulic oil of deep-sea mining machinery. The heat exchanger operates under extreme environmental conditions, characterized by temperatures around 1°C and pressures reaching 600 bar at a depth of 6000 meters. To gain insights into the performance of the shell and tube heat exchanger, the system is modelled and analysed using Ansys FLUENT. The cooling performance is evaluated across multiple scenarios to identify the optimal configuration for deep-sea conditions.

Index Terms **- Deep Sea Technology, CFD Analysis, Heat Exchanger Study, Ansys FLUENT, Optimal Configuration for Deep-Sea Conditions**

I. INTRODUCTION

In the contemporary context of the 21st century, the significance of energy conservation and the efficient functioning of machinery and equipment cannot be overstated. Deep sea mining primarily involves the extraction of mineral-rich polymetallic nodules, including copper, cobalt, nickel, and manganese. The environmental conditions present beneath the sea pose substantial challenges in the modelling, design, and operation of mining equipment. For instance, at a depth of 6,000 meters, the pressure reaches approximately 600 bar, while the temperature hovers around 1°C. The operation of mining machinery at such depths presents formidable obstacles. Figure 1 illustrates the general power flow to the machinery, encompassing the conversion of electrical energy to mechanical energy, followed by the transformation from mechanical to hydraulic energy, and finally from hydraulic back to mechanical energy.

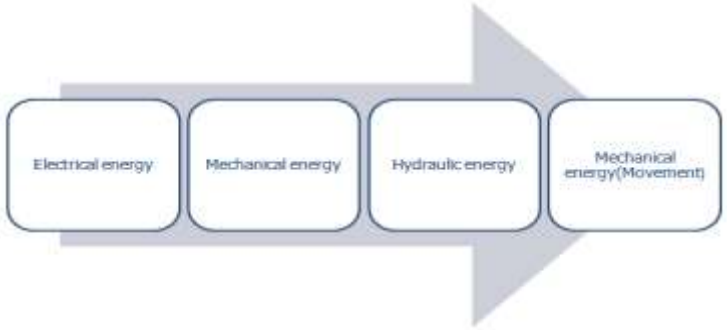

Figure 1-Energy flow

The maintenance of hydraulic oil temperature is crucial for the effective use of energy and the optimal operation of mining machinery in deep-sea environments. In light of the unique conditions present in the deep sea, the design of heat exchangers must take into account various thermal parameters, including heat transfer efficiency and pressure drop, as well as mechanical factors such as stability, strength, and the selection of appropriate materials.

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II. MODELLING

In this instance, a shell and tube heat exchanger has been selected. The specifications pertaining to this heat exchanger can be found in Table 1

Specification	Value	Units
Shell length	1.058	m
Shell Outer dia	0.258	m
Shell inner dia	0.25	m
No of tubes	57	nos
tube dia	0.01905	m
tube pitch	0.02775	m
tube clearance(gap)	0.00745	m
Baffle spacing	0.316	m

The design model of the shell and tube heat exchanger is illustrated in Figure 2

Figure 2-shell and tube heat exchanger

To facilitate the study, the hydraulic oil on the shell side and the sea water on the tube side are modelled separately in FLUENT, given the intricate nature of the problem. The outcomes of these simulations have been successfully acquired. The geometry of the oil domain, representing the shell side fluid, is depicted in Figure 3

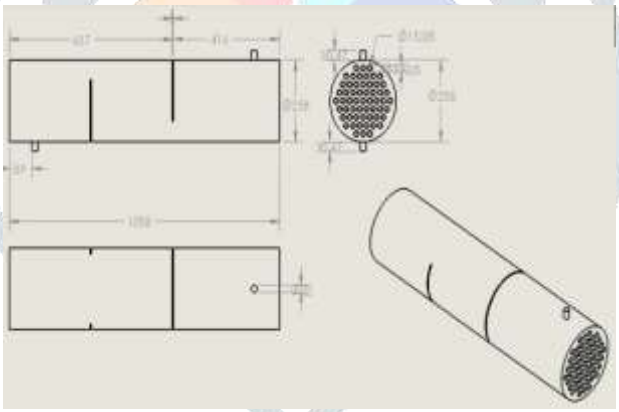

Figure 3-oil domain geometry details

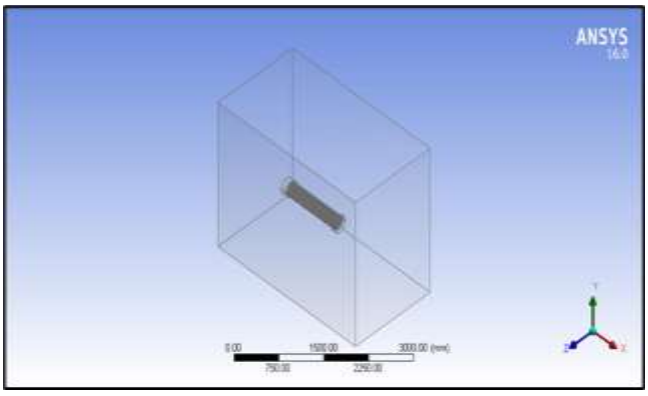

Figure 4 illustrates the domain of seawater that exists outside the shell and tube heat exchanger

In the context of a shell and tube heat exchanger operating under deep-sea conditions, it is important to note that the fluid within the tube side and the surrounding environment are identical. This scenario resembles an oil cooling system facilitated by a fin-type heat exchanger, with the distinction that the configuration employed here is of the shell type.

III. PROPERTIES

A critical aspect of computational fluid dynamics (CFD) analysis involves the accurate identification and importation of material properties. In this context, the properties of seawater, oil, and shell material are essential. Determining the properties of seawater presents a significant challenge, as these properties under deep-sea conditions are derived from a range of studies and empirical correlations. The properties relevant to the seawater domain utilized in the CFD analysis are detailed in Table 2. Additionally, the shell is constructed entirely from stainless steel, with its properties outlined in Table 3.

SEA WATER PROPERTIES

Property	Value	Unit
Pressure	600	bar
Density at 600bar	1055	kg/m^3
Temperature	1	C
Depth	6000	m
Salinity	34.69	g/kg
Thermal Conductivity	5.75111E-05	$wcmdeg^{-1}$
Thermal Conductivity at 600bar, 1 deg C	0.577	W/mK
Specific Heat (Cp)	3980	J/kgK
Viscosity	0.00177157	Pa s

The properties of seawater, including density, viscosity, and thermal conductivity, are not easily accessible; therefore, correlations and existing literature were utilized to ascertain these values. The chart presented in Figure 5 was utilized for the determination of the viscosity of seawater.

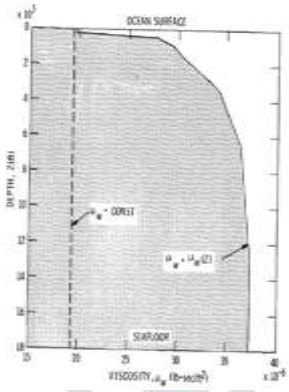

Figure 5.i viscosity vs depth

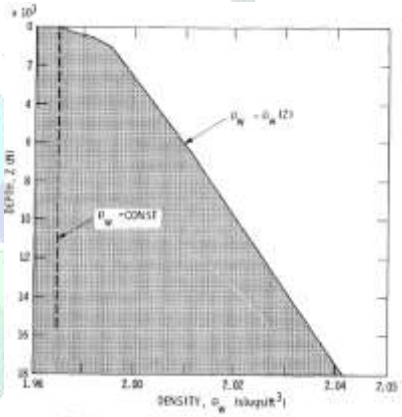

Figure 5.ii density vs depth

The correlation employed to ascertain the thermal conductivity of seawater at a temperature of 1°C and a pressure of 600 bar is as follows

$$K= (5.5289\times10^{(-3)}) + 3.4025\times10^{(-7)}P+1.8364\times10^{(-5)}T-3.3058\times10^{(-9)}T^3) \times 10^{(-5)}$$

The Dorsey relation is employed to investigate the correlation of seawater density with respect to fluctuations in salinity, temperature, and pressure, with particular attention to salinity levels of 31 to 39 g/kg and temperatures from 0 to 22°C

Stainless Steel Properties

Density	7865	kg/m^3
Specific heat	502.58	J/kgK
Thermal Conductivity	40	W/mK

In this simulation, the hydraulic oil employed is ester oil ES32, conforming to ISO 32 grade specifications. The relevant properties of this oil are outlined in Table 5.i Viscosity plays a vital role, as it is significantly influenced by both temperature and pressure. The correlation provided by P. W. Gold et al. is utilized to ascertain the viscosity of hydraulic oil ES32 ISO 32 grade in relation to these factors.

Properties of oil at 65 C 10 bar

Density	879	kg/m^3
Viscosity	0.014253	Pa.s
Specific heat(Cp)	2.428	kJ/kgK
Thermal Conductivity(k)	0.11	Wm/C

IV.OPERATING AND BOUNDARY CONDITIONS

A. Operating Condition

The cooling system functions under deep-sea environmental conditions characterized by a temperature of 1°C and an ambient pressure of 600 Bar. Figure 6 illustrates the operational parameters for the shell and tube heat exchanger. A critical aspect of the analysis is the velocity of ocean currents, which fluctuates with depth. Near the surface, the current velocity is higher, while it diminishes at depths exceeding 2000 meters and remains relatively stable above 4000 meters, averaging around 0.20 m/s. The relationship between current velocity and depth is depicted in Figure 7. It is important to highlight that the flow of the fluid within the tubes is influenced by the relative motion of the mining machine against the current velocity, with the mining machine moving at approximately 0.15 m/s and the current velocity being about 0.20 m/s

This study examines three distinct scenarios to analyze the behavior of the heat exchanger:

1. The operation of a shell and tube heat exchanger with the flow moving in the same direction as the current velocity.
2. The operation of a shell and tube heat exchanger with the flow moving against the current velocity.
3. An analysis focused solely on the heat transfer characteristics of the fluid on the shell side, specifically hydraulic oil.

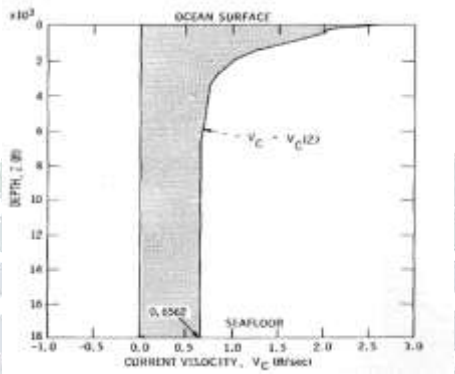

Figure 7-Current velocity Vs Depth

B. Boundary Condition

1.Sea water Domain

In the analysis of the seawater domain, as outlined in Table 2, the interior wall is influenced by a convective boundary condition alongside a singular layer of thermal conduction, characterized by a thermal conductivity of 40 W/m K. The fluid on the shell side is hydraulic oil, which exhibits a convective heat transfer coefficient of 6.5 W/m^2 K. This coefficient was determined using both the Kern method and the Donohue equation, yielding nearly identical results. Figures 8 and 9 illustrate the configuration of the seawater domain and the boundary conditions for scenarios with and against ocean currents, respectively. The inlet current velocity is established at 0.20 m/s, while the shell wall is presumed to move at an absolute velocity of 0.15 m/s in both scenarios.

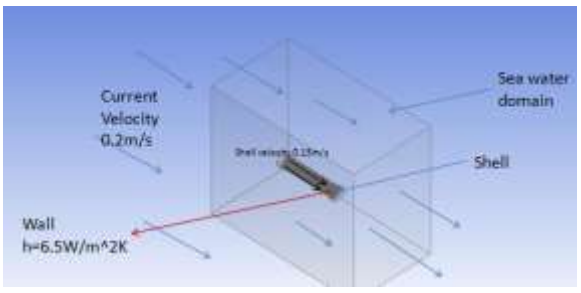

Figure 8-Sea Water Domain Flow with current

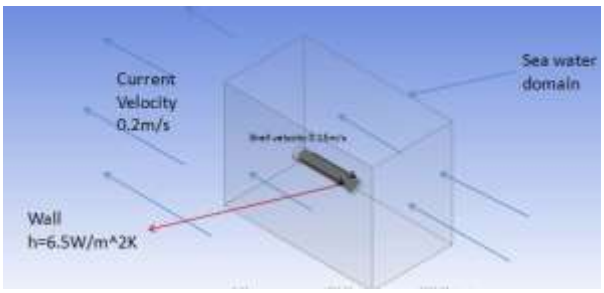

Figure 9-Sea Water Domain Flow against current

2.Oil domain

Figure 10 illustrates the internal oil domain (fluid on the shell side), which experiences an inlet flow rate of 70 liters per minute, under a pressure of 10 bar and a temperature of 338 K. The outlet is characterized by outflow boundary conditions. Both the outer wall (shell wall) and the inner wall (tube wall) are considered fixed, with thermal boundary conditions that include convection and a layer of conduction. The heat transfer coefficient for the tube wall, representing the tube side fluid, is determined using the Dittus-Boelter correlation, yielding a value of 40.82 W/m²·K. The outer shell, modeled under flow over a cylinder conditions, exhibits a convective heat transfer coefficient of 209.25 W/m²·K, as calculated using the Churchill-Bernstein correlation.

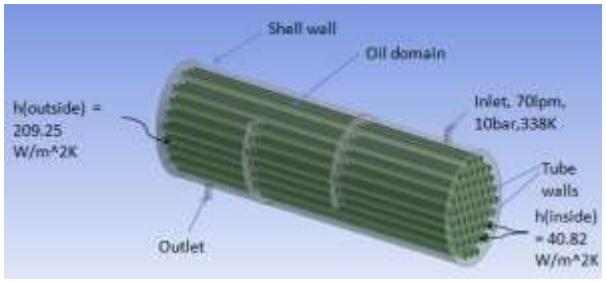

Figure 10-Sea Water Domain Flow against current

V.RESULTS AND DISCUSSION

Figure 11 illustrates the velocity distribution within the XY plane of the shell and tube heat exchanger under the current operational conditions. In contrast, Figure 12 presents the temperature distribution in the same plane. It is evident that the temperature profile at the inlet is significantly low, closely resembling the temperature of seawater. However, while there is a temperature increase at the outlet, this rise is not substantial, resulting in inadequate heat transfer efficiency. Additionally, Figure 11 indicates that the flow dynamics under the current conditions have been effectively captured, revealing that the velocity within the inner tubes is approximately 0.201 m/s, characterized by laminar flow and minimal wall shear. The wall shear in this flow condition is notably low. Figure 13 depicts the wall shear associated with the flow under the current conditions.

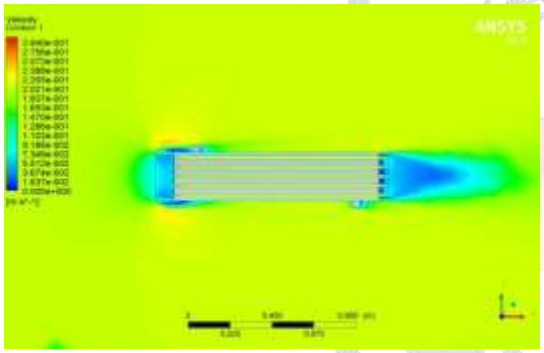

Figure 11-Sea Water Domain Velocity Contour Flow with current

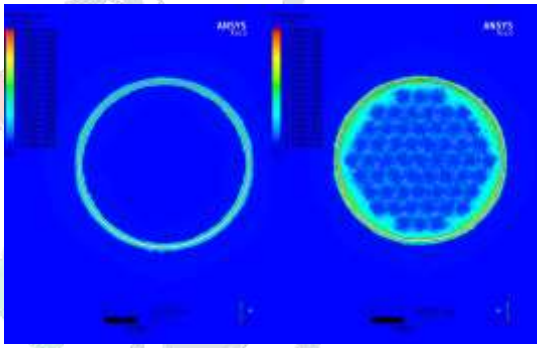

Figure 12-Sea Water Domain temperature contour Flow with current

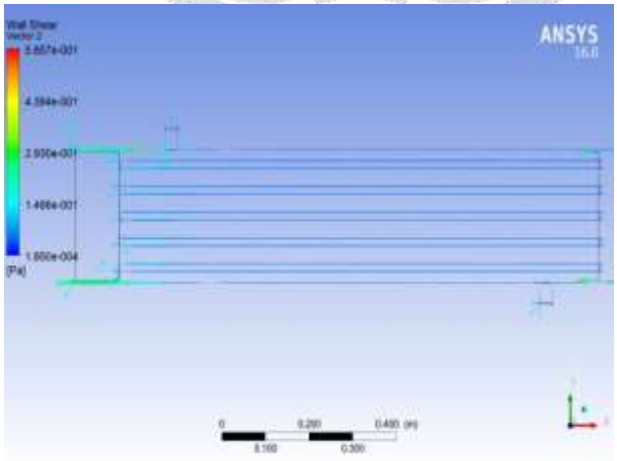

Figure 13-Sea Water Domain wall shear Flow with current

C. Sea water Domain -Flow against the current

Figure 14 illustrates the velocity distribution within the XY plane of the shell and tube heat exchanger operating under opposing flow conditions. Figure 15 presents the temperature distribution at both the inlet and outlet. Figure 16 depicts the wall

shear stress associated with the flow under these conditions. It is evident that turbulence is present in the model when the flow is against the current, as indicated by the fluctuations in velocity at the inner tubes of the heat exchanger, which is further corroborated by the wall shear depicted in Figure 16. Additionally, the temperature of the seawater begins to increase upon reaching the inlet; however, there is no substantial rise in temperature observed in the seawater. The temperature increase within the seawater domain for opposing flow conditions ranges from 6 to 8 K, whereas for the flow with the current, it is approximately 3 to 4 K. Despite the greater temperature increase observed in the opposing flow scenario, the overall effectiveness remains lower.

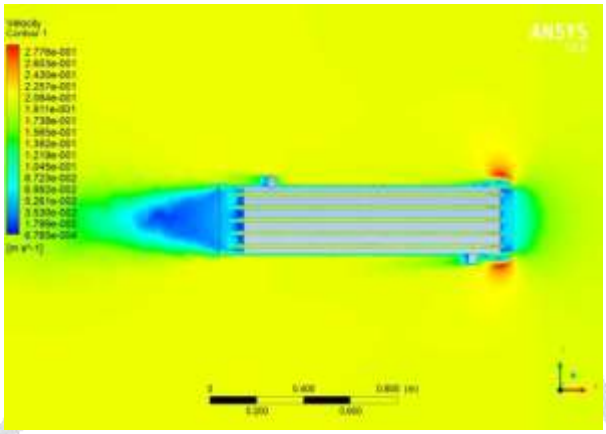

Figure 14-Sea Water Domain velocity contour Flow against current

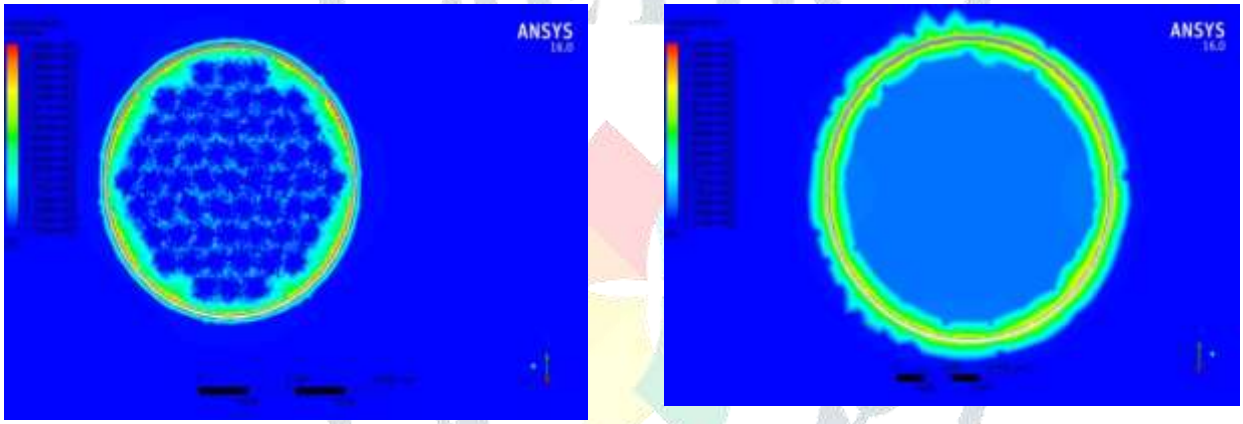

Figure 15-Sea Water Domain temperature contour Flow against current

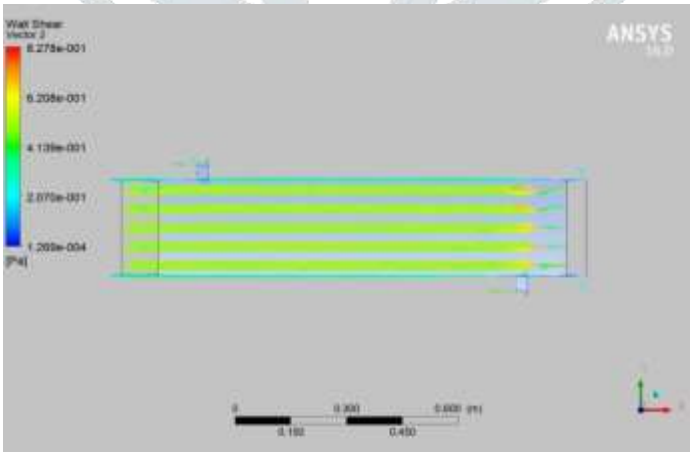

Figure 16-Sea Water Domain wall shear Flow against current

D. Oil Domain

Figure 17 illustrates the velocity contours at three distinct sections of the domain, demonstrating that the flow is effectively captured by the model. This observation is further supported by the velocity streamlines presented in Figure 19. The temperature contour depicted in Figure 18 reveals that the temperature at the oil inlet side is approximately 338 K, which gradually decreases towards the outlet, where the temperature ranges from about 334 K to 328 K, indicating a significant reduction. It is important to note that the heat transfer coefficient for the tube wall is approximately 40 W/m²K, while the shell wall heat transfer coefficient is 209 W/m²K.

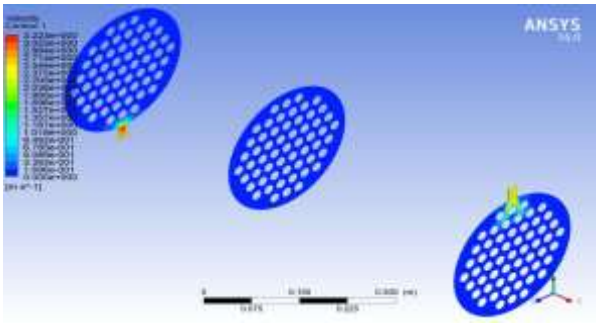

Figure 18-Oil Domain velocity contour

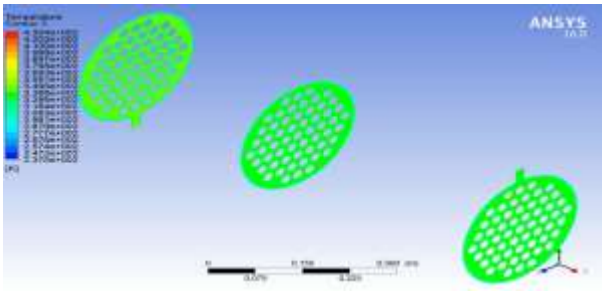

Figure 18-Oil Domain temperature contour

The significant heat transfer coefficient adjacent to the shell wall results in a lower temperature observed near the outer shell wall.

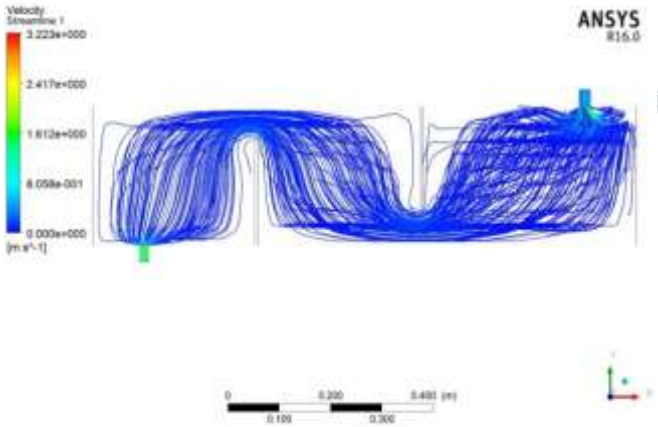

Figure 18-Oil Domain velocity streamline

IV. CONCLUSION

This research on the cooling system indicates that the heat exchanger operates in a manner comparable to a shell and tube heat exchanger. Nevertheless, the optimal configuration for the observed conditions resembles that of a typical oil cooling heat exchanger with fins, similar to those found in motorcycles. Furthermore, the inability to accurately simulate the complexities of a deep-sea environment has resulted in an unclear understanding of the actual performance. The findings of this study offer insights into the general behavior of heat exchangers in deep-sea conditions.

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