Thermal Analysis and Management for an Autonomous Underwater Vehicle

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Abstract – *Electrical, Electronics, Mechanical and Mechatronics systems with moving parts functioning inside the pressure hull of an Autonomous under water vehicle produces and emits heat while functioning in the enclosed space. There is a need to estimate the heat that is generated and to ensure that the temperature inside the pressure hull is maintained within the acceptable limit during the defined endurance of the vehicle.*

In this paper an attempt has been made to study and assess the heat and temperature variation of each sub system of Autonomous underwater vehicle, while functioning separately and as a whole system for various operating conditions through experimentation and thermal simulation using numerical and theoretical means. Methods for heat dissipation for maintaining the temperature inside the pressure hull within the permissible limits also has been studied and reported. Further, an attempt has been made to arrive at a simulation model for predicting the thermal behavior of the vehicle at different operating conditions.

Key Words**: Thermal analysis, heat load, thermal management, heat dissipation, phase changing materials.**

1. INTRODUCTION

An autonomous under water vehicle (AUV) is a self propelled, unmanned underwater robot that has a mission control that is preprogrammed or adaptive in real time. AUVs forms part of a large group of undersea systems known as unmanned under water vehicles. In military applications, AUVs are more often referred as unmanned under sea vehicles (UUVs). These are unmanned and self propelled vehicles which can operates independently for a period of few hours to several days.

These underwater systems consists of pressure hull, control system, propulsion system, power system[9], computer systems used for emergency underwater applications to face several challenges. While the battery[4] is discharging or charging within the sealed enclosure, it releases heat energy in terms of chemical reaction. The heat produced by the battery and moving systems is trapped in the enclosure due to lack of thermal management and free air cooling. The built-up heat energy is extremely dangerous and detrimental to the health of the battery cells. One of the most common causes of failure of the battery is high temperature. Battery failure[11] by heat can be caused by charging discharging at high currents as well as built up thermal energy from its surroundings. Therefore, it is crucial to monitor the temperature of the batteries within the safety limits. Failure to regulate and control the temperature in the casting could spell disaster for the entire system of the AUV. Methods for heat dissipation[2] for maintaining the temperature inside the pressure hull within the permissible limits also has been studied and reported. Further, an attempt has been made to arrive at a simulation model for predicting the thermal behavior of the vehicle at different operating conditions. Hence, thermal management is important due to the high energy content and risk of rapid temperature development in the high current range. Thermal management also has a significant influence on the useful life of the components and ensures fault free operations for extended periods of time.

1.1 OBJECTIVE AND SCOPE OF WORK

The aim of the thesis is to estimate and asses the heat while working with different operating conditions. By estimating the heat from the experiments, we are suggesting the different heat reduction techniques like active air cooling and passive air cooling with PCM[3] based thermal management system.

The scope of work is to estimate the temperature acceptable limit of vehicle which is around 50-55 degree centigrade. If the temperature rise is observed to be beyond the estimated acceptable limit, an attempt will be made to introduce heat sinks and other heat dissipation techniques. In this paper an attempt will be made to arrive at a simulation model for predicting the thermal behaviour of the vehicle at different operating conditions. We can also use this thermal model for predicting the thermal behavior of the static, dynamic conditions of any system which are producing heat.

1.2 PROBLEM DEFINITION

Firstly we are taking a static system as a room building and analyse the heat load calculations at different operating conditions. In the second step we are taking a dynamic system like car with air as a medium and analyse how the heat balance method [1], [5] is used in the cabin while car is in moving condition. In the third step we are taking a system as closed cylindrical shape of a steel bottle and analyse how can we dissipate the heat energy to the atmosphere of a system with water and air as a medium. Placing small heat sources like batteries connected to the series of LED bulbs, small heating bulb connected to the battery, heating coil, motor connected with battery etc. within the bottle and analyse the heat dissipation separately and as a whole systems.

1.3 APPROACH

In this paper we are considering a prototype of underwater vehicle as a steel bottle moving with small propeller in which small heat sources are added to estimate the heat and dissipation of the heat by using the towing tank and wind tunnel experiments. The same results are compared with theoretical and ANSYS.

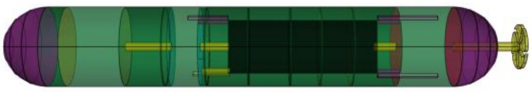

Fig-1: AUV design in AUTOCAD

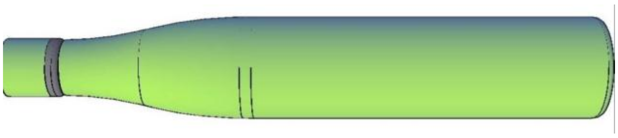

Fig-2: Prototype of AUV

2. ESTIMATION OF THERMAL LOADS

2.1 THEORETICAL ANALYSIS

Condition: static

Material: stainless steel

Free convection

Properties are to be evaluated at film temperature

T_f=$((To + Tamb)|2)$=49°C

Properties at film temperature [6]

Density, ρ =995 kg/m^3

Dynamic viscosity, μ=0.0006537 kg/m sec

Thermal diffusivity α=0.1544*10^{-6} m^2/sec

Prandtl number, Pr=4.34

Specific heat, C=4178 J/kg k

Thermal conductivity, K of steel=80-100 W/m-k

Kinematic viscosity, ν =0.6357*10^{-6}

Nusselt number Nu_x=0.6(Gr*Pr) $^{0.2}$

Consider constant wall temperature and constant heat flux.

Grashof number Gr*=$(g\beta qx^{\wedge}(4)|kv)$

q=heat flux=hAΔT

q= ((2*0.628)/Δx)*(2*3.14*0.035)*22

Δx=1.639

Heat flux q=6.569 w/m^2

Grashof number, Gr*=0.00337

Nusselt number, Nu_x=hD/k

Heat transfer coefficient, h=342.42 W/m^2-k ; Bi<0.1

Density (ρ) of stainless steel=7480kg/m^3

Lumped heat analysis is valid otherwise we will go for heisler chat [6].

$(T - Tamb|To - Tamb)=e^{(-(hAt|\rho vCp)}$

T at 5 min =43˚C

T at 10 min=37˚C

T at 15 min=35˚C

T at 20 min=34˚C

T at 25 min =33˚C

T at 30 min=32.5˚C

Material: stainless steel

Condition: dynamic

Forced convection

Generalised equation

Nu=C.$Re^{0.805}$ $Pr^{0.333}$

Properties are to be evaluated at film temperature T_f=$((To + Tamb)|2)$=50˚C

Properties at film temperature

Density, ρ =989 kg/m^3

Dynamic viscosity, μ=0.000571 kg/m sec

Thermal diffusivity, α=0.1544*10^{-6} m^2/sec

Prandtl number Pr=3.02.

Specific heat C=4178 J/kg k

Thermal conductivity steel=80 to 100 W/m k

Kinematic viscosity v=0.578*10^{-6} m^2/sec

Reynolds number Re= $\rho vD/\mu$

Re=60621.716

Nusselt number Nu=272.106

Heat transfer coefficient h=33041506 W/m^2k

Boit number B_i>0.1

Fourier number F_o= $(\alpha\tau/Ro^2)$ =0.03

Here, Boit number greater than 0.1 so we will use for heisler chat from heat and mass transfer data book [6].

Temperature variation at a specific time is given as follows

$(T - Tamb|To - Tamb)$=0.25

T at 5 min =41.5°C

T at 10 min=36°C

T at 15 min=34.5°C

T at 20 min=33°C

2.2 NUMERICAL ANALYSIS

To get the temperature variation using ANSYS 18.1, firstly design the steel bottle in AUTOCAD 2019.

2.2.1 Modeling of bottle in AUTOCAD 2019

The dimensions are taken from the experimental piece by cutting the bottle, Open the AUTOCAD 2019; click on the NEW on the tool bar then a window will be popped up. Change the system of units to CM using the command UN then press enter. Now click on the line command and draw the half section of the bottle using line command. Now click on the revolve command on tool bar and select the objects to revolve then press enter then give the angle of rotation as 360 degrees then press enter, the half will be rotated to 360 degrees to make a solid body of bottle, then Bottle shape is created .To see the bottle body click on isometric orientation. Now save the file as .iges or.stp.

2.2.2 Modal Analysis procedure in ANSYS

Open the ANSYS 18.1. Drag the fluent analysis system into the project schematic window. Rename the system according to geometry file that will be imported into that system and steel material can be added to the geometry further. Give the element size in body sizing as 0.2 mm. Click on UPDATE button to create mesh for the bottle. Now double click on setup for giving boundary conditions to the geometry. Finally we are getting temperature results once we run the calculation.

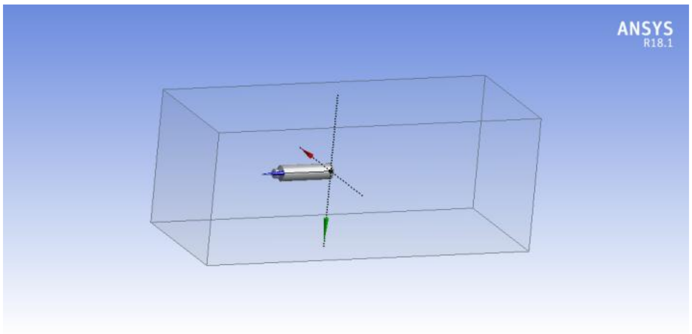

Fig-3:Bottle with enclosure

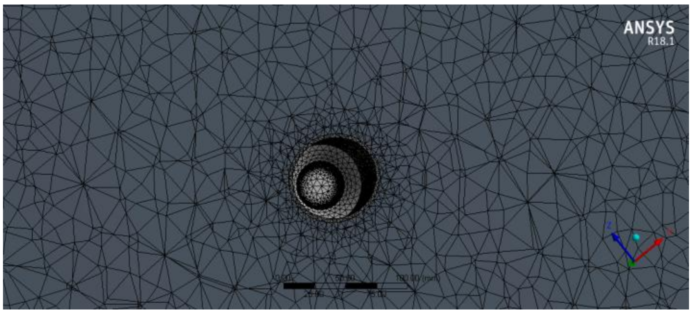

Fig-4: Meshing sectional view

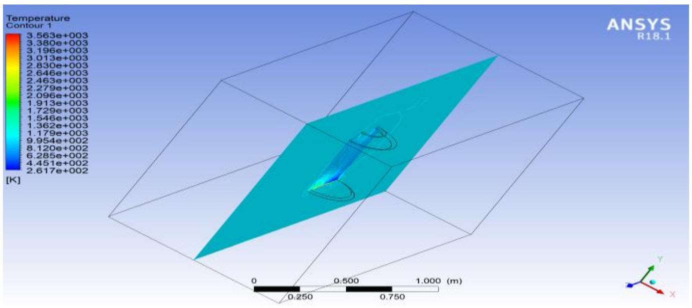

Fig-5: Temperature countour

3. THERMAL MANAGEMENT

According to the difference of the heat transfer medium, the lithium-ion battery thermal management can be broadly classified into two categories i.e. i) Active cooling and ii) Passive cooling[8]. In active cooling, external aid is required to run the cooling system. Active cooling is mechanically assisted, independent on working conditions and easily controllable. By using active cooling, the main advantage is that desired temperature of the component can be controlled independently to that of surroundings. Various types of active cooling techniques are used to dissipate heat from the electronic components such as fan assisted cooling, spray cooling, jet-impingement cooling, micro-channel based, single and multi-phase cooling etc. In spite of their effective heat removal capacity, active cooling technologies may not be preferred due to issues such as maintenance, noise and vibrations etc.

Some of the problems can be avoided by using passive cooling techniques. In passive cooling heat transfer dissipation is not assisted by any external means. Passive cooling system is noise free and has low maintenance when compared to that of active cooling techniques. Even though the passive cooling system has less heat dissipation capacity compared to active cooling systems passive cooling systems are only preferred because of low cost, quiet operation and reliability. Various types of passive cooling techniques are preferred for electronic components such as heat sinks, heat pipes, heat spreaders, PCMs[3] etc. In most of electronic components, heat is extracted from the device by placing heat sinks on it. The general pattern of heat sink is that it is a metal device with number of fins. The reason for effective heat transfer of thermal energy to the surroundings is die to the arrangement if fins. The effectiveness of a heat sink material is directly proportional to its thermal conductivity. The heat transfer by using heat sinks results free convection. Heat pipe is also widely used passive cooling technique, by structure it is a sealed tube with interior wall structure made of a highly conductive material. In mobile applications, heat spreading materials is being used for heat dissipation and to increase the heat dissipation capacity the number of layers should be increased which is limited due to space constraint. Practically passive cooling technique is more promising option for thermal management of electronic components than active cooling but it has less heat dissipation capacity. In passive cooling such trade-offs can be overcome by integrating heat sinks and heat pipes with PCMs. Therefore PCM technology[3] can be considered as an attractive solution for thermal management in challenging applications. Liquid cooling means that the heat transfer medium circulated in a battery group is liquid. The liquid usually has a much larger heat transfer coefficient than air. The thinner liquid boundary layer which makes its effective thermal conductivity higher than air does. According to whether the liquid is directly contacted with the battery, the liquid cooling is divided into direct-contact cooling and indirect-contact cooling. The heat transfer medium used in direct-contact cooling is insulating mineral oil. Indirect-contact cooling usually uses water and ethylene glycol as heat transfer medium. Indirect-contact type liquid cooling should ensure liquid pipeline to have good sealing performance and ensure that the direction of pipeline is reasonable in order to achieve good effect of temperature control. So, indirect-contact type liquid cooling is demanding for the battery box design and processing. Direct contact type liquid cooling utilizes mineral oil with high viscosity. That means it needs a larger pump power to operate, which is very unfavorable for the driving range of vehicle. From the above information we can know the deficiencies of the traditional active battery thermal management: The system is complex, occupies large space and needs for mechanical devices and additional power to operate them; the heat released by the battery fails to recycle, but only damages the battery. Fail to achieve energy saving and emission reduction.

The thermal management system with PCM material cooling is to absorb the heat of the battery by latent heat of PCM material in the phase change process and prevent the battery temperature from rising too fast. PCMs are equivalent to the energy storage tank. It can not only reduce the temperature difference between monomers, but also store energy in cold environment, and it can also transmit the energy into the battery so as to achieve the thermal insulation effect and improve the performance of battery in cold environment. From the point of view of saving energy and improving the driving range of vehicles, the PCM based thermal management system of lithium-ion battery has better cooling effect and thermal insulation effect in cold environment.

3.1 PCM based thermal management system

The present study aims to address the usage of PCMs with their advantages and disadvantages for the thermal management of electronic components. PCM based heat sinks can be an alternative technique for effective dissipation of heat and maintain safer temperature range for the electronic devices. Phase change material (PCM) which melts and solidifies at a certain temperature. It is capable of storing energy during melting and releasing large amount of energy during solidifying. So, PCMs are classified as latent heat storage. It has many advantages like storing large heat energy with only small temperature changes.

The latent heat storage can be achieved through following phase change solid-solid, solid-gas, solid-liquid and liquid-gas. There is only solid-liquid phase change used in PCM because liquid-gas phase change is not practically used and it requires large volume and high pressure created during gas phase change. Solid-gas transition requires higher heat. Solid - solid phase change are typically very slow. The desirable properties of PCM material used for latent thermal energy system are phase change material, latent heat, thermal conductivity. Phase change materials are divided in to three types and its heat storage capacities are Organics paraffin 125-350 kJ, Inorganic 250 -400 kJ, and Eutectics 100-250 kJ.

The classification of PCMs along with their characteristics, advantages, disadvantages and methods for improvement are presented [12], [13], [14].The major problem with PCMs is their low thermal conductivity. This problem can be alleviated by adding of high thermal conductivity materials (i.e. Thermal conductivity enhancers), nano particles[7], metallic foam matrix and metallic fins[15], encapsulation[16] etc.

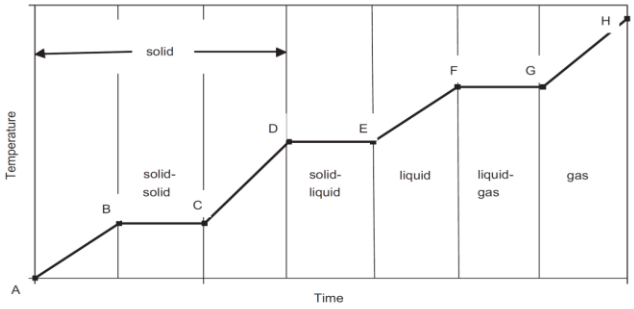

Fig-6: Temperature profile for the phase change materials

4. Experimental validation

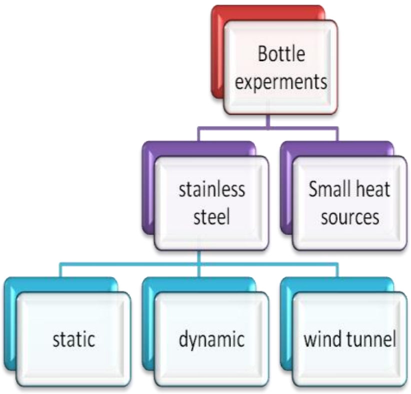

Chart-1: Detailed flow chat of experiments

4.1 stainless steel experiments

Properties and dimensions of a stainless steel

Thermal conductivity, K= 80 to 100 w/m-k

Bottle volume, V=900 ml

Density of steel, ρ=8050 kg/m^3

Diameter, D=7 cm

Thickness, t=3 mm

Length, L=27 cm

Fig-7: Dynamic experimental setup

Material: stainless steel

Condition: Dynamic

Stainless steel experiment readings

T at 5 min= 42°C

T at 10 min=36°C

T at 15 min=34°C

T at 20 min=33°C

T at 25 min=33°C

Material: stainless steel

Condition: Static

Stainless steel experiment readings

T at 5 min=43°C

T at 10 min = 37°C

T at 15 min=35°C

T at 20 min=34°C

T at 25 min=33°C

T at 30 min=32.5°C

Material: stainless steel

Condition: Wind tunnel

Experiment readings

Velocity = 10m /sec

Time 2.00 P.M.

Date 09/05/2019

T_i=58°C, T_{amb}=36°C

Table-1: wind tunnel results

T at 5 min	50˚C
T at 10 min	43˚C
Tat 15 min	42˚C
T at 20 min	41˚C
T at 25 min	40˚C

4.2 Heat sources experiment

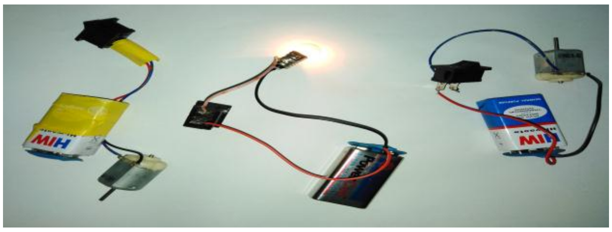

Fig-8: Heat sources

For heat estimation we are considering small heat sources as shown in figure

1. Motors connected to the battery.

2. Small torch bulb connected to the batteries.

3. Battery connected to the series of LED bulbs.

4. Heating coil.

These heat sources are kept inside the steel bottle for the estimation of temperature change inside the bottle with respect to the time. We have been measured the temperature manually by using liquid in glass thermometer. From this experiment we can know that how the heat will be increased in the system.

5. RESULTS AND DISCUSSION

Table-2: Comparison of Dynamic condition results

Stainless steel			Condition: Dynamic
Theoretical in ˚C	Experimental in ˚C	Error in˚C	Error in %
41.5	42	0.5	1.2
36	36	0	0
34.5	34.5	0.5	1.44
33	33	0	0

Table-3: comparison of static condition results

Stainless steel			Condition: Static
Theoretical in ˚C	Experimental in ˚C	Error in ˚C	Error in %
45.4	43	2.4	5.28
36.76	37	0.24	0.6
33.3	35	1.7	5.1
31.92	34	2.08	6.5
31.36	33	1.64	5.2
31.14	32.5	1.3	4.36

Table-4: comparison of wind tunnel results

Stainless steel			Condition: wind tunnel
Experimental in ˚C	ANSYS in ˚C	Error in ˚C	Error in %
50	54	4	7.4
43	48	5	10.41
42	40	2	5
41	39	2	5.1
40	36	4	11.1

The experiment was conducted at a velocity of 0.5 m/sec water flow rate. Temperature variations with time are tabulated and a graph has drawn between them.

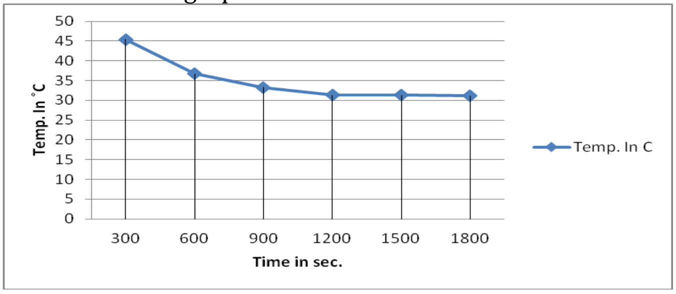

Chart-2: Static temperature variation

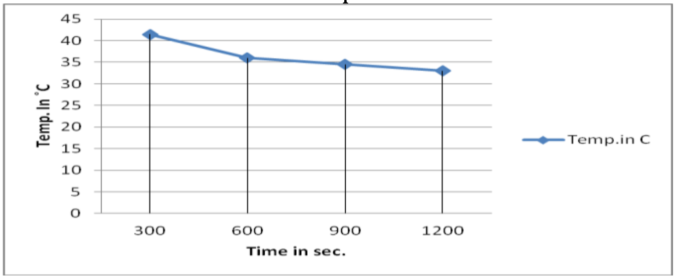

Chart-3: Dynamic temperature variation

6. CONCLUSIONS

This study achieves same through theoretical analysis, simulation, CFD tools and its comparison with the available data obtained through its use and experiments.

The results obtained may be useful for better understanding of heat dissipation, extended life of batteries and systems present in the AUV and for safe reliable operations while AUV in under water.

The study provides an insight of heat dissipation in electronic components and challenges associated with thermal management of electronic devices. Due to the capability of dissipating larger amount of heat at constant temperature, PCMs can be considered as an attractive option for the thermal management of electronic components.

According to literature, PCMs are gaining widespread acceptance by several researchers to dissipate heat from the electronic components. It is expected that PCMs can play a pivotal role in the future cooling techniques due to its attractive features such as noise free, long-term reliability and effective dissipation of heat.

Although organic PCMs has relative low latent heat than inorganic PCMs, due to its good chemical and thermal stability, the application of organic PCMs is much more than inorganic PCMs. To overcome the shortcoming of low thermal conductivity and inflammable, many researchers improved the performance of the PCM by doping with other substances.

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