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Data Analysis and Validation of Acquired Temperature Data on Underwater Platform

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ABSTRACT

Underwater missiles are launched from canister by hot gasses produced by a gas generator. Hot gasses eject the missile out of canister, positioned on an underwater platform in high seas at a depth of 50 m to 70 m. During development phase of submarine launched missile, maximum number of physical parameters related to platform and launching mechanism are acquired on a data acquisition system on-board platform and selected critical parameters are transmitted to control station in real time through an optical data communication link. Missile parameters are recorded on-board and transmitted to the control station by delayed transmission technique once the missile is out of water. Exit velocity of missile is very important parameter for the missile trajectory and range, which depends upon the heat loss in canister and annular gap pressure between missile and canister during the ejection process. Prediction of exit velocity is validated by heat loss calculation by measured temperature at different stations during the test. Temperature measurement is carried out by sensors mounted on the inner wall of canister and also by jumping type of temperature sensor, which measures canister gas temperature. In spite of all efforts, few sensors do not work as expected. It is important to measure various parameters according to instrumentation measurement plan. In case of temperature measurement, sometimes, it is required to predict temperature at location, where sensor was originally not mounted. To validate the recorded test data, another set of data is needed for which one has to wait till next test is conducted that may take years and practically impossible to ensure identical test setup and environmental condition. A mathematical approach to predict temperature at required location and to validate the recorded test data is presented.

Keywords: Underwater platform; Interpolation; Mathematical model; Data validation

1. INTRODUCTION

Submarine launched missiles are launched from underwater platform[1] especially designed for this purpose during development phase. Development of missile is a very complex task, expertise is needed almost in every field of engineering to design various subsystems of missile and launching mechanism. Fully instrumented extensive testing is carried out to evaluate the performance of various subsystems. Based on analysis of data, necessary design modification is carried out and subsystems are qualified for actual use. Missile is positioned inside canister and it is mounted on a launcher fixed inside a container. The gas generator is fitted at the bottom of the canister. Hot gases generated by gas generator eject missile out of canister. The missile is protected from hot gases by obturator which is part of missile. Once the missile is out of canister, underwater booster is ignited that brings missile out of water and obturator is detached. When missile is launched from underwater platform, the missile data is acquired on-board, and transmitted by RF signal by delayed transmission technique. The parameters related to platform, launcher and canister are recorded on-board platform in real time on a data acquisition system. The parameters recorded are gas generator chamber pressure, underwater pressure, strain and vibration. The canister is either made of metal, composite or both. The canister used for present application was made of composite with metallic bottom. The recorded temperature data is required to be validated for its correctness. In this paper, mathematical models based on different interpolation techniques are used to predict the unmeasured temperature at a particular location and for validation of recorded data.

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2. LITERATURE SURVEY AND STUDY

Literature survey was carried out to find various validation methods adopted to validate recorded temperature on the inner wall of canister during launch of underwater missile or similar type of work carried out in this area. Most of the literature available related to missile launch is based on numerical simulation. Selection of underwater missile launch method has been reported by numerical simulation in order to improve the probability of survival of submarine due to high launch back pressure[2] and exhaust. Another work for calculation of guide cone wall temperature of concentric canister launcher considering gas radiation[3] has been reported for vertical launch from a ship. Work on interior trajectory simulation of the gas steam missile ejection[4] for underwater missile has been also reported. No literature is available through open source about validation of recorded temperature data on inner wall of canister due to radiation during missile launch. Lot of work has been reported in the field of climatology, where based on local information and interpolation, prediction has been made related to weather, temperature. Interpolation methods where all data points for a given problem are used during study, result-quality will be influenced by using spatially heterogeneous data. Temperature interpolation based on local information[5] has been carried out by modelling local spatial variation in temperature by taking neighbourhood data points for each grid. Similar type of air temperature measurement requirement in Phoenix spatial interpolation method[6] has been used. To estimate Holidays effects on electricity demand[7] in missing records in time series, different interpolation method has been used. There is no single preferred method for data interpolation for a given problem. Algorithm should be based on actual data, accuracy requirement, time and availability of resources and computational time. One review has been carried out on existing interpolation methods, their performance criteria and uncertainty assessment. As per review, there are numerous criteria for assessing the quality of interpolation exists. In the literature, many redundancies, discrepancies, or subtleties have been found. Different names have been given for same method and different equations has been used for same criteria[8]. To address the present problem, study has been carried out to identify suitable interpolation technique. Data set collected is small due to less duration of test and sampling rate of 1000 samples/s. Local polynomials can be constructed and connected together in lieu of a single polynomial going through all data points. Piecewise Linear Polynomial is local region based polynomial and can be used in mathematical model for given problem. When gas generator is ignited, there is sudden increase in temperature resulting in large variation in recorded data. One statistical module is required to calculate average temperature and Gaussian distribution was found suitable for the data set. Validation of the mathematical model is another important task, as mentioned earlier only one recorded data set is available, it was felt to make another mathematical model based on different interpolation technique and use the same data on both the mathematical models.

3. SYSTEM DESCRIPTION

Underwater platform is positioned in high seas and is connected to control station i.e. a ship, positioned 500 m to 3500 m away from the platform as per testing requirement. The connectivity between underwater platform and control station is by a re-deployable underwater data communication link[9]. All operations are carried out remotely by test controller from the control station. The temperature sensors are mounted at required cross section on the inner wall of canister at different stations and are interfaced to data acquisition system through signal conditioner. The location of temperature sensors mounted on canister is as shown in Fig. 1. Gas temperature inside the canister is measured by jumping type of sensor, which is spring loaded and gets positioned at centre of canister while missile is being pushed out by hot gases. The signal conditioner and data acquisition system is powered by a power management system[10] especially designed for equipment on-board platform. Recorded data is uploaded to control station using high speed data communication link immediately after the test.

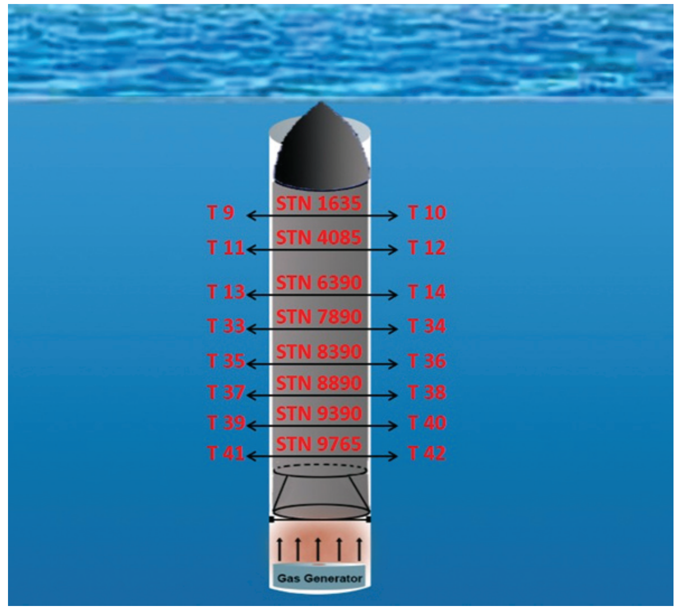

Figure 1. Location of temperature sensors.

4. MATHEMATICAL MODEL AND IMPLEMENTATION

During underwater missile testing, temperature recorded at diametrically opposite cross sections at different locations on inner wall of canister is required to be validated and also to predict temperature at a particular location. This problem can be solved by suitable and appropriate interpolation technique[11]. Care should be taken while selecting suitable interpolation technique that can predict correct data with small data set and consumes minimum computational time.

The values of known function $y = f(x)$ for a given sequence of ordered points $x_0, x_1, \cdots, x_n$, to find $f(x)$ for arbitrary point x, when $x_0 \le x \le x_n$, then this problem is known as interpolation. When $x < x_0$ and $x < x_n$, that is extrapolation where points are outside of given data points.

With $y_i = f(x_i)$, interpolation, is nothing but drawing a smooth curve through the known set of data points $(x_0, y_0), (x_1, y_1), \cdots, (x_n, y_n)$. It is not least square approximation, where drawing a smooth curve that approximates a set of data points with experimental error. Piecewise linear interpolation and Newton interpolation method is considered for the present problem.

4.1 Statistical Module

It is not possible to get homogeneous temperature at every instance during measurement, a statistical module has been implemented to find average maximum temperature.

Let $T_1, T_2, \cdots, T_N$ are N temperature w.r.t. N distances $d_1, d_2, \cdots, d_N$, respectively at different stations. Let Max_T is the maximum temperature, then $Max_T = \underset{i=1}{\overset{N}{Max}}\, T_i$.

Let σ be the standard deviation where $Max_T \in \{T_1, T_2, \cdots, T_N\}$

Therefore, $\sigma = \frac{1}{N-1}\sqrt{\sum_{i=1}^{N}(Max_T - T_I)^2}$

$\{S_T\}$ is defined as the lower and upper range limit i.e. $(Max_T - 3\sigma, Max_T + 3\sigma) = \{S_T\}$

Most of the significant temperature, mostly homogeneous lies within limit of surrounding Max_T which follows the Gaussian distribution as shown in Fig. 2.

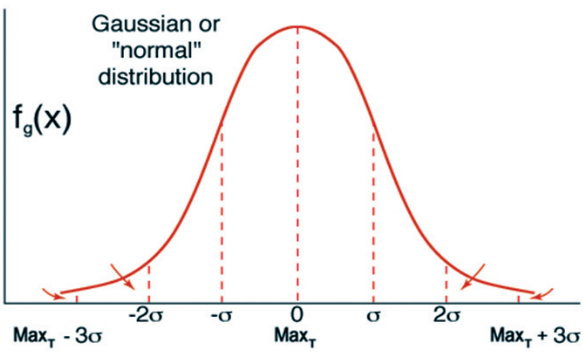

Figure 2. Gaussian distribution.

Temperature values which belongs to set $(Max_T - 3\sigma, Max_T + 3\sigma)$ is calculated as follows:

Let $HT_K, K = 1, 2, ..., M$ are the temperatures which are belonging to the above set

i.e. $HT_K \in [Max_T - 3\sigma, Max_T + 3\sigma]\ \forall K$

i.e. collection of all temperatures which are satisfied to

$Max_T - 3\sigma \le HT_K \le Max_T + 3\sigma\ \forall K$

The mean value of all $HT_K, K = 1, \cdots, M$ is defined as

$MT_d = \frac{1}{M}\sum_{K=1}^{M} HT_k$ Therefore, MT_d is the mean temperature of the homogeneous region at a certain distance d.

Let, $MTd_1, MTd_2, \cdots, MTd_N$ are the mean temperatures of the homogeneous region at distances $d_1, d_2, \cdots, d_N$ respectively. So considering the points as follows:

$(d_1, MTd_1), (d_2, MTd_2), \cdots, (d_N, MTd_N)$ which are represented as $(x_1, y_1), (x_2, y_2), \cdots, (x_N, y_N)$.

4.2 Piecewise Linear Interpolation

Piecewise Linear polynomial is a local region based polynomial using the points $(x_1, y_1), (x_2, y_2), \cdots, (x_N, y_N)$ and considering the piecewise linear interpolation technique using the pair of points

$\{(x_1, y_1), (x_2, y_2)\}, \{(x_2, y_2), (x_3, y_3)\},$
$\cdots, \{(x_{N-1}, y_{N-1}), (x_N, y_N)\}$

Now the equation of the line passing through (x_1, y_1) and (x_2, y_2) is $y(x_1 - x_2) - (y_1 - y_2)x = x_1 y_2 - x_2 y_1$ (1)

Similarly the equation of this line passing through (x_2, y_2) and (x_3, y_3) is

$$y(x_2 - x_3) - (y_2 - y_3)x = x_2 y_3 - x_3 y_2 \quad (2)$$

The last equation will be

$$y(x_{N-1} - x_N) - (y_{N-1} - y_N)x = x_{N-1} y_N - x_N y_{N-1} \quad (N)$$

So each equations $1, 2, \cdots, N$ are the N linear equations and it is called piecewise linear interpolation.

Using these equations, the temperature of any unknown distance can be calculated. For example, let at point $(x_1^{'}, y_1^{'}) \in \{(x_1, y_1), (x_2, y_2)\}$, where $x_1 \le x_1^{'} < x_2$, and $y_1 \le y_1^{'} < y_2$,

So the temperature at distance $x_1^{'}$ can be given by formulae

$$y_1^{'} = \frac{y_1 - y_2}{x_1 - x_2} x_1^{'} + \frac{x_1 y_2 - x_2 y_1}{x_1 - x_2}$$

Similarly, for any others points which belongs to any intervals, the temperature at a specific distance can be calculated.

4.3 Newton Polynomial

The Newton polynomial is an interpolation method in which lower triangular system of linear equation is solved by forward substitution. The interpolating polynomial can be represented as follows:

$$P_n(x) = C_0 + C_1(x - x_0) + C_2(x - x_0)(x - x_1) + \cdots + C_n(x - x_0)\cdots(x - x_{n-1}) ,$$

where $(x_0, y_0), (x_1, y_1), \cdots, (x_n, y_n)$ are $(n+1)$ points.

The above expression is a polynomial of degree n. The $(n+1)$ unknown co-efficient denoted by C_i can be found by substituting the points (x_i, y_i) for $i = 0, 1, \cdots, n.$

So, $y_0 = C_0,$

$$y_1 = C_0 + C_1(x_1 - x_0),$$
$$y_2 = C_0 + C_1(x_2 - x_0) + C_2(x_2 - x_0)(x_2 - x_1),$$
$$\vdots \qquad \vdots \qquad \vdots$$
$$y_n = C_0 + C_1(x_n - x_0) + C_2(x_n - x_0)(x_n - x_1) + \cdots + C_n(x_n - x_0)\cdots(x_n - x_{n-1})$$

$$\begin{bmatrix} 1 & 0 & 0 & \cdots & 0 \\ 1 & (x_1 - x_0) & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & (x_n - x_0) & (x_n - x_0)(x_n - x_1) & \cdots & (x_n - x_0)\cdots(x_n - x_{n-1}) \end{bmatrix}$$

$$\begin{bmatrix} c_0 \\ c_1 \\ \vdots \\ c_n \end{bmatrix} = \begin{bmatrix} y_0 \\ y_1 \\ \vdots \\ y_n \end{bmatrix}$$

Piecewise linear and Newton interpolation technique require less number of data samples with smaller interval for interpolation, can be used in present problem to get accurate estimated values.

5. TEST RESULTS AND DATA VALIDATION

The temperature data acquired during the test is presented. The data pertaining to odd numbered and even numbered sensors is as given in Tables 1 and 2, respectively. For calculating average temperature, the recorded data between 0.5 s and 2.5 s is considered. The average temperature computed by statistical module is as shown in Fig. 3. To validate the test data, two mathematical model have been used which validate each other along with recorded data. Result by mathematical model based on Piecewise linear and Newton interpolation technique are as shown in Figs. 4 and 5, respectively. The comparison of average temperature computed by both the models is as shown in Fig. 6. It is observed that there is difference in recorded temperature between odd numbered and even numbered sensors. The difference is due to flow of hot gases filling the canister while missile is being pushed out of canister. Sensor at location T41 and T42 shows very high temperature as these sensors are mounted closer to gas generator. It is clearly seen from the data as hot gases are moving upwards and losing heat due to radiation, canister temperature is decreasing. As there is difference in measured value by sensors mounted diametrically opposite, interpolation result is plotted separately. It is seen in the Fig. 6 that over plots of result by Piecewise linear and Newton interpolation is exactly matching for both odd numbered sensor and even numbered sensor data. The only location where it does not match is T39 and T40.

Since, interpolation is possible only between two point and interpolated data is dependent on the values of T41 and T42, the location of sensor which is nearer to gas generator, temperature will be very high and considering this point in interpolation may introduce some error. Figs. 7 and 8 are plotted without considering the values of T41 and T42. A close match is seen in the data predicted by both the mathematical models using different interpolation method for recorded test data set.

6. CONCLUSIONS

(i). It is possible to calculate temperature at a location where thermocouple has not worked, faulty measurement

Table 1. Canister wall temperature data of odd numbered sensors

Time (s)	T9	T11	T13	T33	T35	T37	T39	T41
0.500	01.416	00.731	04.638	16.870	20.738	13.001	58.071	302.796
0.600	00.189	02.335	08.880	23.854	33.411	13.001	71.107	343.426
0.700	04.506	06.097	12.130	27.346	38.679	16.494	78.875	379.006
0.800	11.481	08.808	15.325	29.137	37.786	15.598	79.768	394.498
0.900	13.640	12.571	15.876	33.435	44.750	11.300	80.661	393.697
1.000	15.798	12.018	19.621	32.629	46.446	13.001	78.071	371.172
1.100	17.404	14.175	19.621	34.330	44.750	12.106	73.696	345.264
1.200	16.296	16.333	19.621	34.330	39.482	12.106	72.000	326.211
1.300	17.957	16.333	19.621	35.226	42.161	12.106	68.518	310.630
1.400	17.957	15.227	20.172	34.330	41.268	12.106	68.518	295.050
1.500	79.404	15.780	19.071	34.330	41.268	11.300	65.929	282.942
1.600	13.640	16.333	20.668	32.629	39.482	12.106	65.929	274.306
1.700	13.086	16.333	19.071	34.330	38.679	10.405	62.446	264.779
1.800	11.481	16.333	19.621	31.733	40.375	11.300	62.446	254.363
1.900	08.768	14.729	20.172	31.733	36.893	11.300	62.446	250.890
2.000	06.650	14.175	18.575	30.838	36.893	13.001	61.554	246.617
2.100	07.163	12.018	16.427	31.733	36.893	12.106	62.446	329.672
2.200	04.506	12.018	15.876	31.733	31.786	13.001	65.929	172.187
2.300	04.506	10.996	15.325	29.943	41.268	13.001	65.929	121.172
2.400	04.506	08.808	14.774	30.838	40.375	10.405	55.482	120.281
2.500	03.399	07.702	12.681	28.241	41.268	11.300	46.821	110.755

Table 2. Canister wall temperature data of even numbered sensors

Time (s)	T10	T12	T14	T34	T36	T38	T40	T42
0.500	00.133	01.148	10.224	22.964	43.946	45.192	91.589	298.321
0.600	01.735	07.550	16.131	33.411	51.804	52.048	106.321	326.089
0.700	03.126	07.550	20.989	38.679	61.357	62.464	115.071	349.571
0.800	11.689	15.608	28.497	37.786	62.250	64.245	132.393	332.161
0.900	13.291	19.362	27.945	44.750	69.214	71.991	139.357	343.500
1.000	16.550	19.914	29.546	46.446	66.536	75.463	130.696	358.232
1.100	18.705	22.011	30.651	44.750	64.839	71.991	124.625	339.125
1.200	18.152	20.962	29.050	29.482	61.357	71.991	118.464	325.286
1.300	21.356	20.011	27.945	24.161	60.464	71.100	115.875	311.357
1.400	19.754	20.410	27.945	41.268	58.768	67.717	111.589	300.911
1.500	14.948	21.514	27.393	14.268	56.982	65.937	107.214	293.054
1.600	11.689	19.914	27.945	39.482	56.179	63.355	102.929	280.911
1.700	68.883	19.362	26.896	38.679	56.179	61.574	101.143	273.946
1.800	05.281	20.410	26.334	40.375	50.393	60.773	98.554	267.071
1.900	05.778	20.962	26.896	36.893	52.696	58.191	95.964	260.170
2.000	04.728	18.258	29.050	36.893	51.804	57.301	93.375	259.214
2.100	03.623	13.456	30.651	36.893	51.804	57.301	94.179	251.357
2.200	02.021	12.407	30.098	37.786	51.804	70.299	85.518	201.893
2.300	03.126	08.102	25.792	41.268	50.911	68.519	69.893	164.482
2.400	02.021	09.151	19.885	40.375	50.108	71.100	63.108	152.339
2.500	01.524	08.102	15.579	41.268	48.321	44.302	55.161	123.679

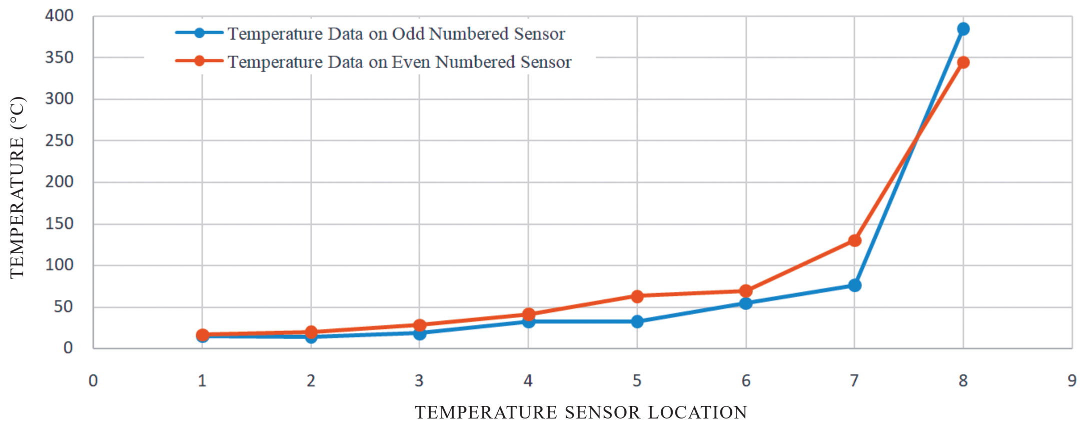

Figure 3. Average temperature value by statistical module.

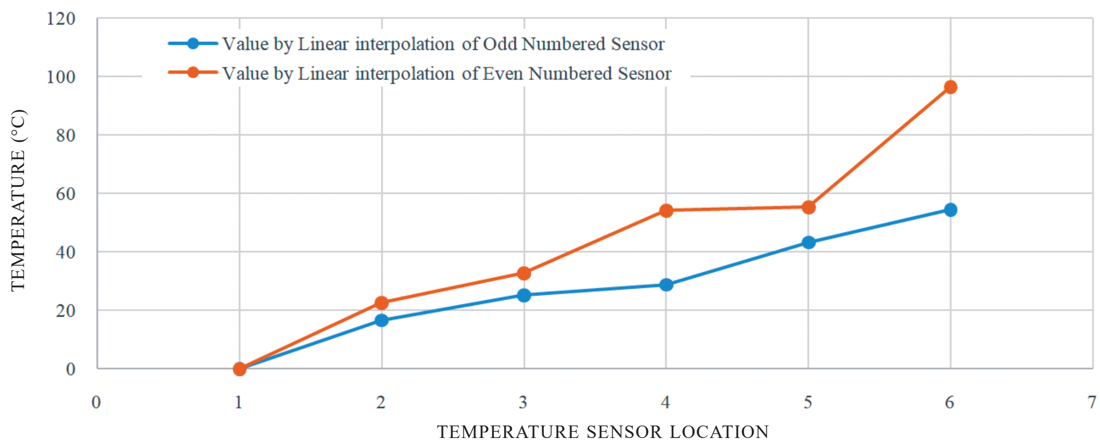

Figure 4. Average temperature value by linear interpolation.

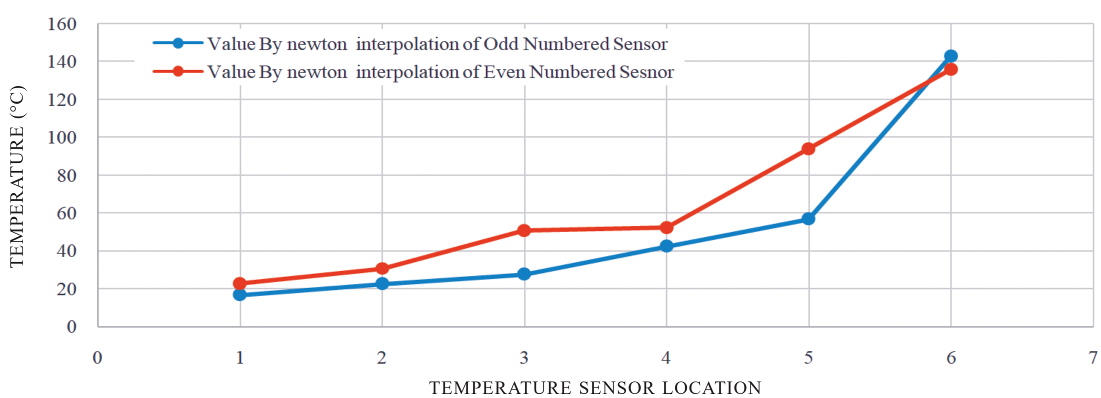

Figure 5. Average temperature value by Newton interpolation.

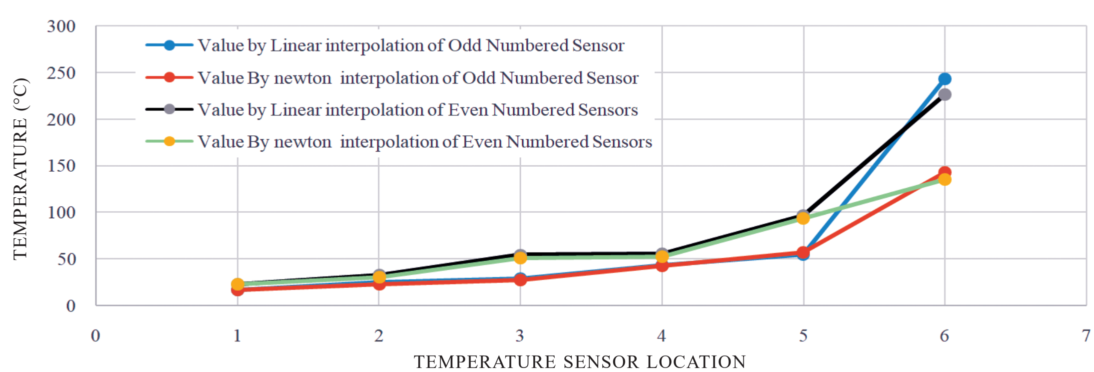

Figure 6.Comparison of data with linear and Newton interpolation.

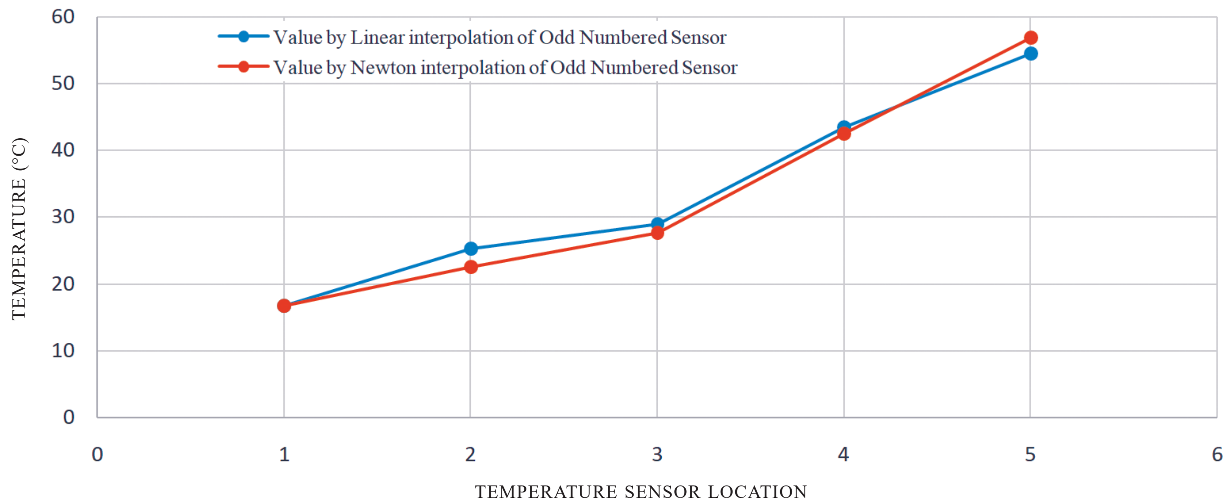

Figure 7. Comparison: Linear and Newton interpolation of odd numbered sensors.

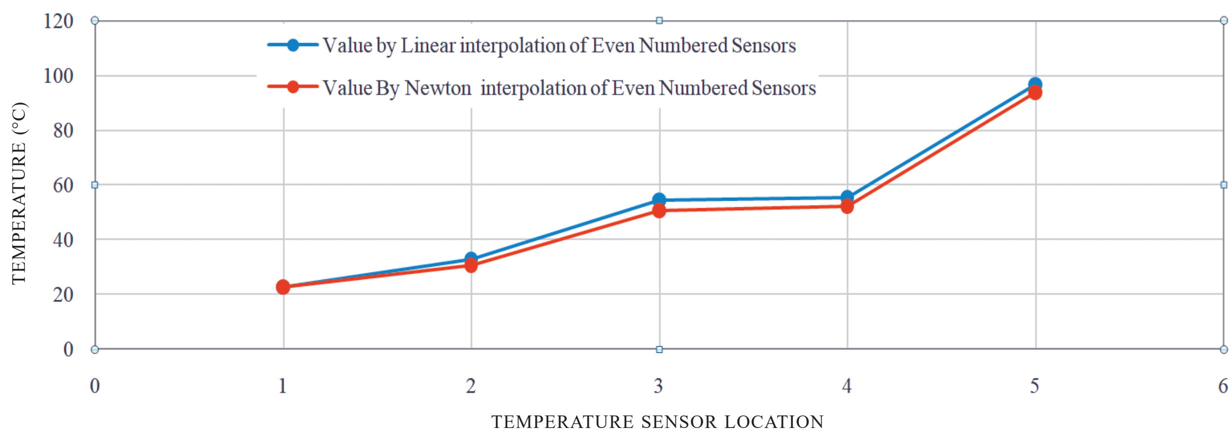

Figure 8. Comparison: Linear and Newton interpolation of even numbered sensors.

and where temperature sensor was not mounted as per measurement plan

(ii). Sensors mounted at diametrically opposite location ideally should be equal. It is observed that temperature is equal at location (T9, T10) and (T41, T42) only, at other locations, it is not equal due to the flow of hot gases and gases not being in equilibrium

(iii). Based on the result and analysis, it is suggested that designer should measure temperature data at a station diametrically opposite at four locations and at many stations

(iv). In absence of another set of test data, it is possible to validate one model by another model using available data set. One mathematical model based on piecewise linear interpolation technique was made and recorded temperature data was validated. Piecewise linear interpolation model was validated by another model based on Newton interpolation technique. It is observed that there is a close match in data obtained by both the models.

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Mr Arun Kumar received his BE (Electronics and Telecommunication Engineering) from BIT, Ranchi University and MTech in Electronics Instrumentation (by research) from NIT, Warangal and currently pursuing his PhD from NIT, Warangal. Presently working as General Manager in DRDO-DIC, Panagarh. His research interests : Data communication, data acquisition, underwater instrumentation, high speed visual imaging, design and development of test jigs for missile systems.
He is designer of underwater instrumentation system. The data was acquired and validated using mathematical model by him in the current study.

Dr L. Anjaneyulu, did his BTech from Nagarjuna University, MTech in EI from NIT Warangal. Currently working as Associate Professor, Department of Electronics and Communication Engineering, NIT, Warangal, He has published 15 paper in journals and 20 paper in conferences. He evinces keen research interests in the area of : Antenna design, electromagnetic fields and waves, microwave and radar, computer networks, network programming, fuzzy logic, and neural networks.
He has reviewed the work and given many valuable suggestions in the current study.