

DETERMINATION OF THE PHYSICAL PROPERTIES OF SALINE WATER AT DIFFERENT TEMPERATURES AND CONCENTRATIONS

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Abstract: A quick and accurate determination of the physical properties of seawater represents an important aspect of research dealing with processes that involve wide variations in temperature, pressure, and concentration. The physical data should be cast in a form readily compatible with the development of mathematical models associated with the synthesis and optimization of industrial processes involving heat and mass transfer operations on seawater. In this work, previously reported experimental data pertaining to the variation of seawater physical properties are correlated into simple empirical mathematical forms enabling their straight forward inclusion into mathematical models associated with seawater and brackish water desalination.

Keywords: PHYSICAL PROPERTIES, SALINE SOLUTION, SEA WATER, BRACKISH WATER

1. Introduction

Getting the physical properties of seawater has always been a problem for researchers who work on any process that involves wide variations of temperature and concentration. These properties are very important in developing and optimizing mathematical models, which should be as accurate and efficient as possible. These data are essential for many industrial processes like seawater desalination or other processes that involves heat or mass transfer. In this work, experimental data for the variation of some physical properties of saline water with temperature and concentration were used to get empirical mathematical correlations that are used in mathematical models for water desalination or any other process that involves changes in these variables.

2. Physical Properties

2.1. Vapor Pressure

Experimental data for the variation of water vapor pressure with both temperature and concentration from three different sources are compared [1,3,4,6], and then one set of data are used to get a mathematical correlation.

Stoughton and Lietzke [1] made some experimental work, resulted in a relation between the concentration of salts in water and the ratio between the vapor pressure of sea salt solutions and pure water at any temperature as shown in Table 1. Their work was implemented by calculating the values of the vapor pressures of salt solutions using Raoult's Law and comparing it to experimental results and fitting the results to get the relation that is independent of temperature. They worked at a temperature range from 25°C to 175°C and at concentrations up to 28.2% of salts by weight.

Table 1: Relation between water salinity and the vapor pressure of saline solution and pure water [1]

S*10 ²	LOG(P/P ₀)
0	0
3.5	-0.0089
9.6	-0.0257
16.5	-0.0466
21.6	-0.0637
28.2	-0.0833

Where P - the vapor pressure of sea salt solution, P_0 -vapor pressure of pure water, S - salinity (the salt content in mass fraction).

Antoine's constants [2] of pure water, which are used in Antoine's equation to relate the vapor pressure to the temperature, were obtained as shown in Table 2. The vapor pressure of sea salt water was calculated at the given concentrations at a temperature range from 0°C to 175°C. The results are shown in Table 3.

Table 2: Water Antoine's Constants

A	18.3036
B	3816.44
C	-46.13

$$(1) \ln P_0 = A - \frac{B}{T+C}, \text{ Where } P_0 \text{ -the vapor pressure of pure water (mmHg), } T \text{ - the water temperature (K).}$$

Table 3: Vapor Pressure of Sea Salt Solutions

T (°C)	P ₀ (mmHg)	S*10 ²				
		3.5	9.6	16.5	21.6	28.2
		LOG(P/P ₀)				
		-0.0089	-0.0257	-0.0466	-0.0637	-0.0833
		P (mmHg)				
0	4.44851412	4.358278	4.192905	3.995903	3.841625	3.672104
5	6.390711335	6.261079	6.023504	5.740493	5.518858	5.275325
10	9.041602585	8.858199	8.522076	8.121671	7.808101	7.463549
15	12.60999822	12.35421	11.88543	11.327	10.88968	10.40914
20	17.35146458	16.9995	16.35446	15.58605	14.98429	14.32307
25	23.57527946	23.09707	22.22065	21.17663	20.35902	19.46063
30	31.65178229	31.00974	29.83309	28.4314	27.33368	26.12752
35	42.02005403	41.1677	39.6056	37.74475	36.28746	34.68619
40	55.1958541	54.07624	52.02433	49.57999	47.66575	45.56239
45	71.77973585	70.32372	67.6553	64.47656	61.98718	59.25184
50	92.46525752	90.58965	87.15225	83.05745	79.85067	76.32707
55	118.0472037	115.6527	111.2643	106.0366	101.9426	97.44413
60	149.4297311	146.3986	140.8436	134.2261	129.0438	123.3494
65	187.6343541	183.8283	176.853	168.5436	162.0363	154.8861
70	233.8076875	229.065	220.3732	210.0191	201.9104	193.0007
75	289.2288674	283.362	272.6099	259.8015	249.7708	238.749
80	355.3165773	348.1092	334.9002	319.1652	306.8425	293.3023
85	433.6356115	424.8396	408.7191	389.5157	374.4768	357.9521
90	525.9029151	515.2353	495.6848	472.3953	454.1565	434.1158
95	633.9930456	621.1328	597.5641	569.4879	547.5005	523.3407
100	759.9430125	744.528	716.277	682.6232	656.2677	627.3083
110	1074.407126	1052.613	1012.672	965.0924	927.831	886.8882
120	1488.98165	1458.778	1403.425	1337.486	1285.847	1229.106
130	2026.14599	1985.05	1909.73	1820	1749.73	1672.52
140	2711.20266	2656.21	2555.42	2435.36	2341.33	2238.01
150	3572.26093	3499.8	3367	3208.8	3084.92	2948.79
160	4640.17588	4546.05	4373.55	4168.07	4007.14	3830.32
170	5948.44593	5827.79	5606.65	5343.23	5136.93	4910.25
175	6703.87138	6567.89	6318.67	6021.79	5789.3	5533.83

Another set of experimental data was obtained by Arons and Kientsler in 1954 [3] based on a previous work of Higashi [4]. They got the values of vapor pressure at a temperature range from 0°C to 175°C and chlorinity range from 0 to 160 parts per thousand in the form of vapor pressure lowering from values of pure water. The results were obtained using a differential manometer that compares the vapor pressures between two samples, pure water and a salt solution, in two different cells. According to Wooster, Lee, and Dietrich [5], the relation between salinity and chlorinity is given as follows.

$$(2) S=1.80655 \times 10^{-3} Cl, \text{ where } Cl \text{ - chlorinity}$$

The actual values of vapor pressures versus temperature at different chlorinities and salinities are shown in Table 4.

Table 4: Vapor Pressures of Sea Salt Solutions[3]

Cl	S *10 ²	T, °C	0	25	50	75	100	125	150	175
0	0	P ₀ (mmHg)	4.4485	23.575	92.465	289.23	759.94	1740.7	3572.3	6703.9
10	1.8	P (mmHg)	4.4085	23.375	91.725	287.24	755.19	1731	3553.8	6670.9
20	3.6		4.3685	23.145	90.925	284.83	749.74	1719.6	3531.3	6631.3
30	5.4		4.3285	22.895	89.965	282.15	743.54	1706.7	3506.5	6585.9
40	7.2		4.2785	22.655	88.885	279.24	736.04	1691.4	3477.8	6535.9
50	9		4.2285	22.335	87.715	276.03	727.84	1674.2	3444.3	6476.9
60	10.8		4.1785	21.995	86.505	272.63	718.94	1654.5	3404.3	6405.9
70	12.6		4.1285	21.695	85.055	268.13	707.94	1632.7	3359.3	6329.9
80	14.5		4.0685	21.325	83.615	264.13	697.74	1608.7	3315.3	6246.9
90	16.3		4.0085	20.905	82.165	259.13	685.24	1583.7	3264.3	6152.9
100	18		3.9285	20.505	80.765	254.43	672.54	1556.7	3209.3	6063.9
110	19.9		3.8585	20.055	78.865	248.13	656.94	1523.7	3147.3	5954.9
120	21.7		3.7685	19.545	77.265	242.63	642.94	1492.7	3086.3	5835.9
130	23.5		3.6585	19.075	75.265	235.53	624.94	1453.7	3004.3	5703.9
140	25.3		3.5685	18.585	73.665	230.83	608.94	1423.7	2942.3	5588.9
150	27		3.4285	18.055	71.565	223.83	589.94	1375.7	2850.3	5443.9
160	28.9		3.3085	17.435	69.665	216.43	571.94	1332.7	2750.3	5263.9

The third set of experimental data obtained by Hassan in 1979 [6] directly links the vapor pressure to the temperature and concentration of saline water. Her experimental work was done using water and NaCl solution in a wetted-wall column and a packed column. Table 5 shows the values at temperature range from 0°C to 110°C and salinity from 0 to 0.25.

Table 5: Vapor Pressure of Sea Salt Solutions [6]

S*10 ² T, °C	0	2.5	5	7.5	10	12.5	15	20	25
0	4.6	4.5	4.4	4.4	4.3	4.2	4.1	3.8	3.5
10	9.2	9.1	8.9	8.8	8.6	8.4	8.2	7.7	7.1
20	17.5	17.3	17	16.7	16.4	16.1	15.7	14.8	13.6
30	31.8	31.4	30.9	30.4	29.8	29.2	28.5	26.8	24.7
40	55.3	54.5	53.6	52.7	51.7	50.7	49.5	46.6	43
50	92.5	91.2	89.7	88.1	86.4	84.7	82.8	78.1	72.2
60	149.5	147	145	142	140.7	137	134	126	117
70	233.8	230	226	222	218	21	209	198	183
80	355.5	350	344	338	332	325	318	301	279
90	526	517	509	500	491	481	470	445	414
100	760	748	736	723	710	695	680	643	599
110	1075	1057	1040	1022	1003	983	961	911	849

A comparison between the three sets of data was done to choose the most suitable one that can be used in any mathematical model. Figures 1-3 show the values of vapor pressure versus concentration for the three data sets, each figure is plotted at different temperatures, 0°C, 50°C, and 100°C, which are the common temperatures in the three sets.

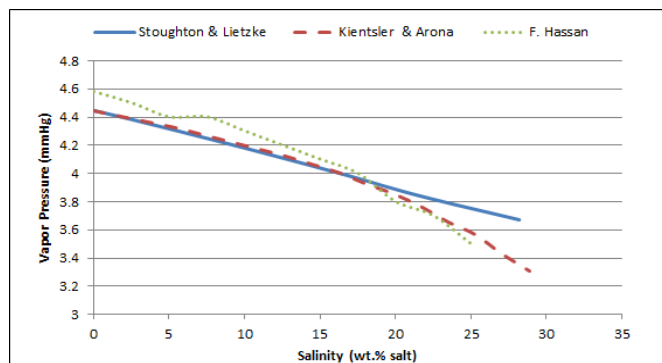


Fig.1 Vapor Pressure of Salt Solutions at 0 °C

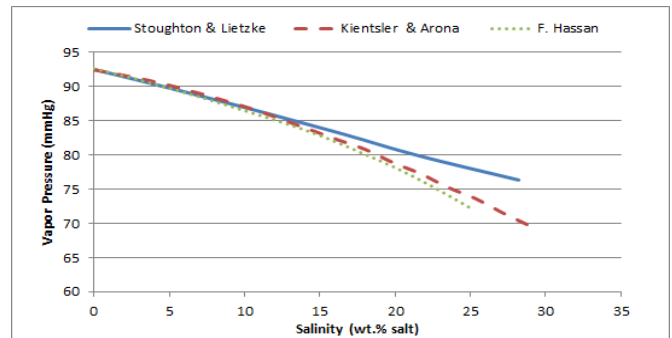


Fig.2 Vapor Pressure of Salt Solutions at 50°C

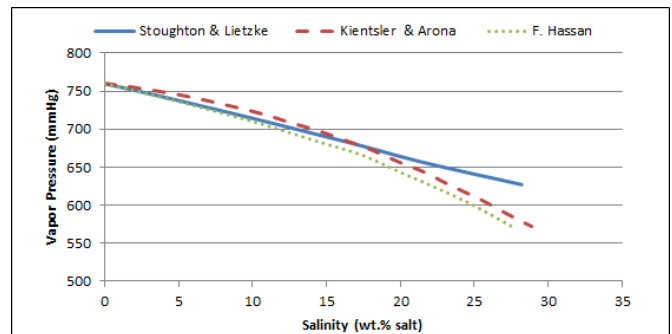


Fig.3 Vapor Pressure of Salt Solutions at 100°C

It may be concluded from Figures 1-3 that at high salt concentrations the data of Stoughton and Lietzke diverges from the compared sets of data, while at relatively low salt concentrations the results are very close. Accordingly, either the data of Kientsler and Aronor or F. Hassan may be used. The data of F. Hassan, being slightly more conservative will be correlated in the following section. This data will be fitted for a temperature interval between 30°C and 100°C, and for a salinity of 0 to 0.05.

Data fitting was executed using MS-Excel on two steps. The first step was to fit the data into three third order polynomial equations, one for each concentration (equation (3)). Figure 4 shows the three curves from which the three polynomial equations were obtained.

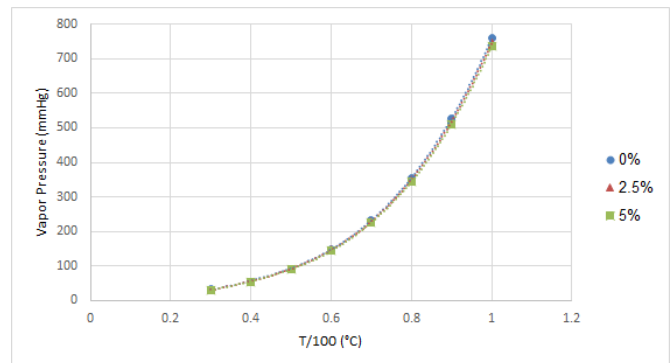


Figure 4 Vapor Pressures of Sea Salt Solutions vs. Temperature at three concentrations

$$(3) P = A \left(\frac{T}{100}\right)^3 + B \left(\frac{T}{100}\right)^2 + C \left(\frac{T}{100}\right) + D$$

Table 6 shows the values coefficients of the A, B, C, and D. **Table 6: Coefficients of Vapor Pressure's Polynomial Equation vs. Temperature**

Coefficients	S*10 ²	0	2.5	5
A		1643	1624.5	1600.5
B		-1498	-1493	-1469.9
C		704.63	703.37	693.39
D		-90.096	-90.417	-89.086

The second step in data fitting is to obtain a relation between these constants with the salinity of water, illustrated in Figure 5.

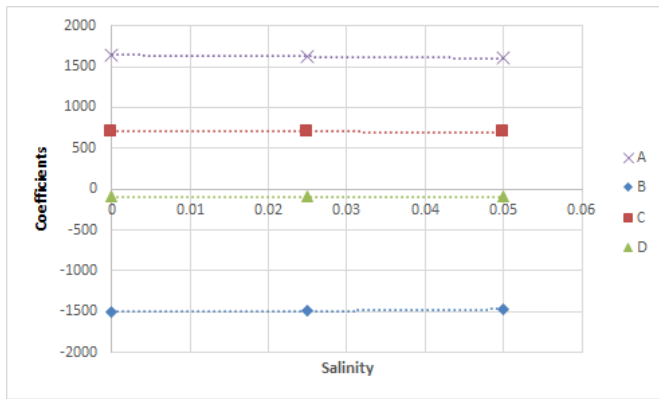


Fig.5 Coefficients of Vapor Pressure's Polynomial Eq. (3) vs. Temperature and Salinity

Vapor pressure can thus be calculated from equation(4):

$$P = (A_2S^2 + A_1S + A_0)T^3 + (B_2S^2 + B_1S + B_0)T^2 + (C_2S^2 + C_1S + C_0)T + (D_2S^2 + D_1S + D_0)$$

The coefficients of the new polynomial equation are shown in Table 7.

Table 7: Coefficients of Vapor Pressure's Polynomial Equation vs. Temperature and Salinity

	Coefficient of S ²	Coefficient of S ¹	Coefficient of S ⁰
A	-0.0044	-0.00063	0.001643
B	1.448	-0.0162	-0.1498
C	-69.76	1.24	7.0463
D	1321.6	-45.88	-90.096

2.2. Specific Heat

Experimental data by Millero et al. [7] for the variation of the specific heat capacity of saline water with temperature and salinity is used to get a mathematical correlation. The specific heat variation with temperature for a range from 0°C to 40°C for salinities up to 0.04 using heat capacity calorimeter was obtained, shown in Table 8.

Table 84: Specific Heat of Sea Salt Solutions

S*10 ² \ T.°C	0	20	35	40	60	80	100	120	140	160	180
0	4.2	4.1	4	4	3.9	3.8	3.7	3.6	3.5	3.5	3.4
20	4.2	4.1	4	4	3.9	3.8	3.7	3.6	3.6	3.5	3.4
40	4.2	4.1	4	4	3.9	3.8	3.7	3.6	3.6	3.5	3.4
60	4.2	4.1	4	4	3.9	3.8	3.7	3.7	3.6	3.5	3.4
80	4.2	4.1	4	4	3.9	3.8	3.7	3.7	3.6	3.5	3.4
100	4.2	4.1	4	4	3.9	3.8	3.8	3.7	3.6	3.5	3.5
120	4.3	4.1	4.1	4	4	3.9	3.8	3.7	3.6	3.5	3.5
140	4.3	4.2	4.1	4.1	4	3.9	3.8	3.7	3.6	3.6	3.5
160	4.3	4.2	4.2	4.1	4	3.9	3.9	3.7	3.7	3.6	3.5
180	4.4	4.3	4.2	4.2	4.1	4	3.9	3.8	3.8	3.7	3.6

The data was fitted into a sixth order polynomial equation by multiple polynomial regression. The coefficients of the equation are shown in Table 9.

$$(5) Cp = \sum_{i=0}^6 \sum_{j=0}^6 (Cp_{ij} S^i T^j)$$

Table 95: Coefficients of the Polynomial Equation of the Specific Heat vs. Temperature and Salinity

		T(j)						
		0	1	2	3	4	5	6
S(i)	0	4.21	-1.18 E-03	1.50 E-05	-5.73 E-08	5.28 E-10	-2.27 E-12	3.75 E-15
	1	-6.66	5.62 E-02	-5.77 E-04	1.79 E-06	-4.25 E-10	6.72 E-13	
	2	14.38	-2.7 E-01	2.45 E-03	-7.29 E-06	2.47 E-10		
	3	-40.4	2.50 E-01	-3.00 E-04	-4.61 E-07			
	4	379.7	-1.38	1.40 E-03				
	5	-1692	2.434					
	6	2920						

2.3. Density

Isdale and Morris [8] tested the variation of the density of saline water with temperature and salinity experimentally. The data includes his experimental work in addition to selected values from the literature to cover a wide range of salinity and temperature. These values are shown in Table 10.

Table 10 - Density of Sea Salt Solutions [8]

S \ T	0.01	0.03	0.035	0.05	0.07	0.09
20	1005.8	1020.8	1024.5	1035.9	1051.2	1066.7
30	1002.8	1017.6	1021.4	1032.6	1047.8	1063.1
40	999.2	1013.9	1017.7	1028.8	1043.8	1059
50	995	1009.7	1013.4	1024.5	1039.4	1054.4
60	990.2	1004.9	1008.6	1019.6	1034.5	1049.4
70	984.9	999.5	1003.2	1014.3	1029.1	1044
80	979	993.7	997.4	1008.4	1023.2	1038.1
90	972.7	987.4	991.1	1002.1	1017	1031.8
100	965.8	980.6	984.3	995.4	1010.3	1025.2
110	958.5	973.3	977.1	988.3	1003.2	1018.2
120	950.7	965.7	969.4	980.7	995.8	1010.9
130	942.4	957.6	961.4	972.8	988	1003.2
140	933.8	949.1	953	964.5	979.9	995.2
150	924.7	940.3	944.2	955.9	971.4	987
160	915.2	931.1	935.1	946.9	962.7	978.5
170	905.4	921.6	925.6	937.7	953.7	969.7
180	895.3	911.7	915.8	928.1	944.4	960.6

The data fitting was executed using MS-Excel on two steps. The first step was to fit the data into six third order polynomial equations, one for each concentration in the table to get a relation between the density and temperature for each concentration, shown in Figure 6.

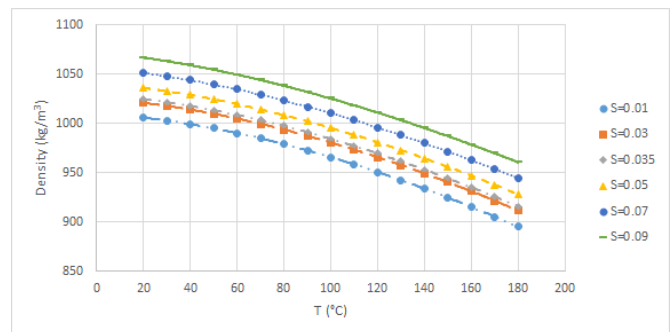


Fig.6 Density of Sea Salt Solutions vs. Temperature

At any of these salinities, density can be calculated from equation (6):

$$(6) \rho = AT^3 + BT^2 + CT + D$$

Table 11 shows the coefficients of the polynomial equations for six different salinities.

Table 61: Coefficients of Density's Polynomial Equation vs. Temperature

S Coeff	0.01	0.03	0.035	0.05	0.07	0.09
A	3 E-06	3 E-06	3 E-06	3 E-06	3 E-06	3 E-06
B	-33 E-04	-32 E-04	-32 E-04	-3 E-03	-29 E-04	-27 E-04
C	-1406 E-04	-1591 E-04	-1613 E-04	-1799 E-04	-2031 E-04	-2338 E-04
D	1009.9	1025.5	1029	1040.7	1056.4	1072.4

The second step is to fit the coefficients B, C, and D obtained in the first step into three third order polynomial relations with the temperature of the water. There was no need to fit the coefficient A into an equation as it is constant with the concentration. Figure 7 illustrates those curves.

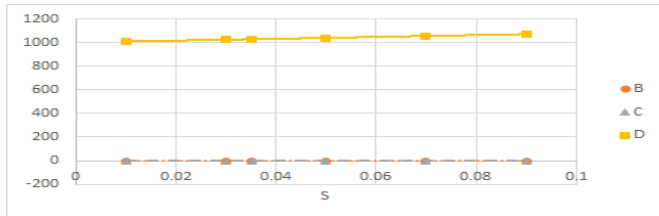


Figure 7 - Coefficients of Density's Polynomial Equation s. Temperature and Salinity

The final correlation takes the following form:

$$\rho = AT^3 + (B_4S^4 + B_3S^3 + B_2S^2 + B_1S + B_0)T^2 + (C_4S^4 + C_3S^3 + C_2S^2 + C_1S + C_0)T + (D_4S^4 + D_3S^3 + D_2S^2 + D_1S + D_0)$$

The coefficients are shown in Table 12.

Table 72: Coefficients of Density's Polynomial Equation

	Coefficient of S ⁴	Coefficient of S ³	Coefficient of S ²	Coefficient of S ¹	Coefficient of S ⁰
B	107.04	-22.001	1.5311	-0.0332	-0.0031
C	-1450.8	266.78	-20.898	-0.3121	-0.1357
D	-271743	58595	-3957.3	866.48	1001.6

2.4. Viscosity

Isdale et al. [9] tested for the variation of the viscosity of saline water with temperature and salinity. This data was measured in a temperature range from 20°C to 180°C for salinities up to 0.15 using master viscometer and pressurized body fall viscometer. The values of viscosities are shown in Table 13.

Table 13 - Viscosity of Sea Salt Solutions [9]

S T	0.01	0.03	0.035	0.05	0.07	0.09	0.11	0.13	0.15
20	1.02	1.06	1.04	1.11	1.16	1.22	1.29	1.36	1.44
30	0.81	0.85	0.86	0.88	0.93	0.98	1.03	1.09	1.15
40	0.67	0.69	0.7	0.73	0.76	0.80	0.85	0.9	0.95
50	0.56	0.58	0.59	0.61	0.64	0.68	0.71	0.75	0.8
60	0.48	0.5	0.5	0.52	0.55	0.58	0.61	0.65	0.68
70	0.41	0.43	0.44	0.46	0.48	0.51	0.53	0.56	0.6
80	0.36	0.38	0.39	0.4	0.42	0.45	0.47	0.5	0.53
90	0.32	0.34	0.34	0.36	0.38	0.4	0.42	0.44	0.47
100	0.29	0.3	0.31	0.32	0.34	0.36	0.38	0.4	0.42
110	0.26	0.28	0.28	0.29	0.31	0.32	0.34	0.36	0.38
120	0.24	0.25	0.25	0.26	0.28	0.3	0.31	0.33	0.35
130	0.22	0.23	0.23	0.24	0.26	0.27	0.29	0.31	0.32
140	0.20	0.21	0.22	0.22	0.24	0.25	0.27	0.28	0.3
150	0.19	0.2	0.2	0.21	0.22	0.23	0.25	0.26	0.28
160	0.17	0.18	0.19	0.19	0.21	0.22	0.23	0.24	0.26
170	0.16	0.17	0.17	0.18	0.19	0.20	0.22	0.23	0.24
180	0.15	0.16	0.16	0.17	0.18	0.19	0.20	0.22	0.23

The data was fitted into a sixth order polynomial equation by multiple polynomial regression. The coefficients of the equation are shown in Table 14.

$$(8) \mu = \sum_{i=0}^6 \sum_{j=0}^6 (\mu_{ij} S^i T^j)$$

Table 84: Coefficients of Viscosity's Polynomial Equation vs. Temperature and Salinity

		T(j)						
		0	1	2	3	4	5	6
S(i)	0	1.6704	-4.51 E-02	7.28 E-04	7.43 E-06	4.62 E-08	-1.59 E-10	2.28 E-13
	1	0.792	-2.23 E-02	9.23 E-04	-1.18 E-05	6.15 E-08	-1.16 E-10	
	2	55	-1.4265	1.07 E-02	-3.57 E-05	4.70 E-08		
	3	-239.5	8.49284	-3.82 E-02	5.12 E-05			
	4	-912.8	-27.396	6.61 E-02				
	5	13321	28.7108					
	6	-34660						

2.5. Thermal Conductivity

Jamieson and Tudhope [10] tested the variation of the thermal conductivity of saline water with temperature and salinity is used to get a mathematical correlation. The experimental data was measured at a temperature range from 0°C to 180°C for salinities up to 0.16. Table 15 shows the values of thermal conductivity in mW/m.K.

Table 15: Thermal Conductivity of Sea Salt Solutions [10]

S*10 ² T	0	2	3.5	4	6	8	10	12	14	16
0	571	568	565	565	561	557	553	549	545	541
20	603	601	599	599	596	593	590	587	584	581
40	630	628	627	627	625	623	621	619	617	614
60	650	650	649	649	648	647	646	645	644	642
80	665	666	666	666	666	666	666	666	665	665
100	676	677	678	678	679	680	681	681	682	682
120	682	684	685	686	688	689	691	692	693	694
140	683	686	688	689	691	694	696	698	700	702
160	680	684	686	687	690	694	697	699	702	705
180	673	678	681	682	686	689	693	696	700	703

The data was fitted into a sixth order polynomial equation by multiple polynomial regression. The coefficients of the equation are shown in Table 16.

$$(9) K = \sum_{i=0}^6 \sum_{j=0}^6 (K_{ij} S^i T^j)$$

Table 96: Coefficients of Thermal Conductivity's Polynomial Equation vs. Temperature and Salinity

		T(j)						
		0	1	2	3	4	5	6
S(i)	0	570.893	1.77376	-7.57 E-03	-1.2 E-05	3.0797 E-07	-1.90 E-09	4.015 E-12
	1	-134.11	1.95142	7.092 E-03	-9.8 E-05	7.1038 E-07	-1.74 E-09	
	2	-941.08	-5.23 E03	-15.36 E-03	-2.5 E-04	2.3667 E-07		
	3	16714.9	226.994	76.176 E-03	7.94 E-04			
	4	-255.6 E03	-1971	-60.98 E-03				
	5	1838.07 E03	5112.74					
	6	-4651.5 E03						

3. Conclusion

Determination of different physical properties of sea water solution is essential for many industrial processes. Different mathematical correlations of the vapor pressure, specific heat, density and viscosity of saline water at different temperatures and salinities have been obtained, based on previous experimental data.

4. References

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