TEMPERATURE CORRECTION IN SHIP AND MODEL RESISTANCE.

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1. — Numerous expressions and tabulations have been given for the change in model resistance due to change in temperature. Most of these suffer from the fact that they are expressed as a percentage of the frictional resistance, when actually an absolute correction to the total specific resistance independent of the relative residuary resistance is undoubtedly the easiest to deduce and to apply.

Let us consider the problem in the light of extrapolator technique. The total specific resistance for any Froude number at the standard temperature 15° C may be written,

$$F_0 = a + b\ R_0^{-1/3}$$

Similarly the value at any other temperature is,

$$F = a + b\ R^{-1/3}$$

the surface of the model in each case being technically smooth and the flow entirely turbulent.

The change in specific resistance is thus given by.

$$F_0 - F = b\ [R_0^{-1/3} - R^{-1/3}]$$

which reduces to,

$$\delta\ F = b\ [I - (\ \gamma/\gamma_0)]\ R_0^{-1/3} = B_0 R_0^{-1/3}$$

and as V and L are constant for each case to be considered this finally reduces to,

$$\delta\ F = b\ [I - (\gamma/\gamma_0)]\ R_0^{-1/3} = B_0 R_0^{-1/3}$$

From this expression the resistance change can be calculated. The variation of kinematic viscosity of fresh water is known between freezing and boiling points; and table I based upon a simpler table given by Goldstein should prove useful in model experiment practice. With the viscosity variation known we can thus calculate the resistance differential from B_0 which equals 340 $[I - (\nu/\nu_0)^{1/3}]$, where 340 is the value given by the extrapolar for a form without edge-effect.

The values of B_0 so found are plotted in fig. 1. This diagram shows that the resistance variation with temperature is not linear. Above 15° C the correction is somewhat less than linear, whilst below the correction is somewhat greater.

To convert these results to δF values they have to be divided by the cube root of the standard temperature Reynolds number; and this clearly exerts a dominating influence on the temperature correction. For example, to correct specific resistance results taken at 20° C to the standard temperature, they must be increased by 0,142 at a Reynolds number of 10^6, by 0,066 at 10^7 and by 0.014 at 10^9: As the corresponding frictional resistances for these Reynolds numbers are 4,600, 2,778 and 1,540 respectively, the corresponding percentage changes will be 3,09, 2,38 and 0.91 respectively. Conservely, to correct results taken at 10° C to the standard a greater correction must be made. This amounts to 0,167 at 10^6, 0,0775 at 10^7 and 0,0167 at 10^9, the respective percentage values being 3,63. 2,79 and 1,07. To facilitate temperature corrections by this method Table 2 giving B_0 values over a range of temperature has been prepared.

2. — It is now of interest to consider existing practice in temperature correction. The latest agreed convention is still that adopted at the 1935 Paris conference of tank superintendents. This gives the correction to the Froude coefficients from the agreed standard temperature of 15° C and refers to both model and ship. The correction is 2,15 percent of the frictional resistance above and below the standard temperature and is completely independent of Reynolds number! It is believed that the correction was originally deduced at the Lichtenrade Tank from tests on a cement model a wide range of temperature.

Use has also been made of the simple term formula for specific resistance to calculate corrections. These are of the general form $F = c\,R^{-n}$. From this it can easily be deduced that the percentage change in specific resistance is given by $[1 - (\upsilon/\upsilon_0)^n]$. From this relation we see that the use of the single term formula results in the percentage change in resistance being independent of Reynolds number, thus implying that the same relative change would take place on both ship and model. It is extremely doubtful whether any evidence is available to substantiate this and it is generally felt that ship results are less sensitive to temperature change. This is discussed later in section 4. However, it is of interest to examine the cases of n equal to one-sixth as substantially found by Hiraga; and one-eighth as found by

Gebers. For the case of one-sixth, the correction for 5° above and below the standard is respectively 2,5 and 2,0 percent. For the one-eighth, the correction in smaller and is respectively 2,0 and 1.5 percent.

When the various temperature corrections in current use are presented in diagram for mto a Reynolds number function base with ordinates of percentage resistance change per 5° C above and below the standard temperature, as is done in fig. 2, the result is rather extraordinary. The two extrapolator curves start from zero at infinite Reynolds number and increase to 4 and 3,5 percent respectively at about 2×10^9 Reynolds number. To show the range of Reynolds number corresponding to a speed-length ratio of 0,50 to 1,0 (in knots-feet) for various length of model, apropriate range lines are shown in the diagram. It is seen from the diagram that the international value of 2,15 percent only agrees with the extrapolar in the large model range of between 10^7 and 10^8. The mean Gebers' value of 1,75 percent requires Reynolds numbers greater than 10^8 for agreement and are therefore clearly too small for model work. Some values given by Payne in the discussion of Lamble's 1932 INA paper are also shown in the diagram. These refer to tests made on the Haslar standard polished brass model « Iris ». Payne did not distinguish between up and down from the standard temperature and his mean results range between 2,20 and 2,85 percent. He stated, however, that for all ordinary correction work itwas sufficiently accurate to use a mean value of 2,7 percent. Baker also used this value at Teddington; and it is seen that for the usual size of model this is also the mean value given by the extrapolator. The results calculated from the Schoenherr formula are also shown. It seen that for most model sizes the Schoenherr values are appreciably below the extrapolator values but agree with the international values for the larger model size. In 1939 Baier published a chart giving the percentage resistance correction back to a standard temperature and over a range of model speed-length product. His data are also shown in fig. 2 and are seeen to lie between the extrapolator and Schoenherr values. A similar chart to the Baier but without any Reynolds number correction, was given by Comstock in his 1942 ASNAME paper. This was for use with 4 foot models and when plotted in our fig. 2 is seen to lie materially below all other results. These Comstock data show that despite deliberate efforts to ensure fully turbulent flow in these small models, the flow cannot be fully turbulent and must be transitional. A more detailed consideration of the transitional state is therefore essential.

3. — It is well known that the specific resistance in mixed laminar and turbulent flow conditions is given by the following relation,

$$F_m = F_t - K/R$$

where F_m is the mean specific restance and F_t the completely turbulent specific restance. K is a factor depending upon the degree of laminar flow in the mixture and is thus zero when the flow is completely turbulent. This expression can be used to deduce the change in specific resistance due to a change in water temperature. We have already determined the change in F_t and it only remains to determine the change in K/R. Calling this δF_1, we have,

$$\delta F_1 = K/R_0 - K/R = - K\ [I - \nu/\nu_0]/R_0$$

The total change in specific resistance for mixed flow is thus given by,

$$\delta F - \delta F_1 = b[I - (\nu/\nu_0)^{1/3}]/R_0^{-1/3} - K\ [I - \nu/\nu_0]/R_0$$

It is probably most convenient to consider this effect of transition flow as a ratio of the laminar to the turbulent term. In this case the ratio reduces to

$$\delta F_1/\delta F = K/b\ R_0^{2/3} \times [I - (\nu/\nu_0)]/[I - (\nu/\nu_0)^{1/3}]$$

For simplicity and for the sake of adopting some arbitrary standard of mixed flow, let us use the Prandtl K value of 1700, which is to be multiplied by 10^3 in our presentation. The value of the ratio thus becomes

$$\delta F_1/\delta F = 1700 \times 1000 \times f(\nu)/340\ R_0^{2/3} = 5 \times 10^3 \times f(\nu)/R_0^{2/3}$$

Now as $f(\nu) = [I - \nu/\nu_o]/[I - (\nu/\nu^{1/3}]$, when $\nu - \nu_o$ the value of $f(\nu)$ becomes equal to 3. We can thus say for small temperature changes that $\delta F_1/\delta F = 15 \times 10^3/R_0^{2/3}$. At a Reynolds of 10^9 the loss in temperature due to mixed flow in thus 1,5 percent; at 10^8, 7 percent; at 10^7, 32,3 percent; and at 10^6 the loss is 150 percent. In this latter case, the range of the 5 foot model, increasing the temperature thus actually increases the resistance. This of course follows at from the nature of the transtion curve. The value of some 30 percent at 10^7 shows the importance of mixed flow even on the 20 foot model.

4. — The findings of the previous section explain how the wide differences in temperature correction shown in fig. 2 are possible. They also show how prevalent mixed flow has evidently been in the past. The continental figures and those of Newport. News also strongly suggest mixed flow, despite in the latter case deliberate attempts being made to induce turbulence. This is evident from the fact that at 10^6 a reduction of 44,5 percent from the full turbulence correction is shown, where as without stimulation a loss of 150 percent could have been expected. This implies that instead of a K value of 1700 one of 500 is being induced. This suggests that as a provisional parameter of turbulence stimulation we can use the ratio, (1700 — K)/1700. Thus in the Newport News case the turbulence stimulation is 1200/1700 or some 70 percent.

Prof. Jack in the discussion of Schoenherr's 1932 SANAME paper, mentioned that Denny's experience over may years since 1883, gave a correction of 2,9 percent for 5° C. As a mean value for a 12 foot model this corresponds exactly to the extrapolator value. One has thus the suspicion that in the early days of the wax model the surface finish did not have the mirror smoothness which is easily and usually obtained today. This improved finish has probably contributed to the apparently increased frequency of laminar flow noticed of recent years. When improved finish is also associated with the use of small models, mixed flow, even with modern methods of turbulence stimulation appears to be very difficult to avoid altogether. The prevalence of low temperature corrections in small model work shows that much more research into turbulence stimulation is urgently required. It is probable that small models should not be given too high a surface finish. Research on this point would also be very valuable.

5. — Very little real evidence is available from full-scale data. As the decrease of viscosity with increase in temperature is less in salt water than in fresh, the temperature effect will also be slightly less. It is actually sufficiently correct to reduce the B_0 values of table II by 5 percent to get the salt water change. These corrected B_0 values will refer to the perfectly smooth ship. For actual ships having a viscous roughness r the correction to specific resistance will be given by,

$$\delta F = .95\ (I + r)\ B_0/R_e^{1/3}$$

Thus with unity roughness and $R_e = 10^9$ the correction from 15° C to 20° C will be $\delta F = 0{,}264$, or 1.4 percent of the frictional plus roughness resistance. For the corresponding smooth surface the percentage is 0,86 percent. This example shows the importance of allowing for viscous roughness in ship model correlation work where temperature correction is necessary. This appears to be particularly true for the change atlantic liner type of vessel where the viscous roughness is approaching and evidently exceeding the value of 2. Kempf's test-plate experiments on the Hamburg are very interesting in this connection. These tests refer to a mean local Reynold's number of 6×10^8; and this would give a smooth specific resistance of 1.469, where as a mean value of 2.14 was obtained, which if there was no hull fouling would correspond to a viscous roughness of 2.5. For 5° C change in temperature a δF value of 0.047 would be expected and this appears to be broadly endorsed of the results.

Where a ship is shell-fouled, resulting in a constant frictional plus roughnes resistance, the temperature correction will, of course be zero. Temperature corrections are chiefly required in the correct analysis of ship trial data when the ship is generally clean and the viscous roughness formula will apply.

Some indirect evidence of the smaller temperature correction in the ship is supplied by the following example. A number of small vessels built for tropical service where the water temperature was about 27° C appeared to have a much lower propulsive coefficient than that predicted from their model experiments if their hull resistance was corrected for temperature at the usual model rate. When the method of this paper were applied the correlation became normal.

At the present moment the overhaul of ship-model correlation is being internationally considered. It is hoped that the foregoing notes will assist the more accurate conduct of the correlation and so hasten the better understanding of the subject.

FIG. 1

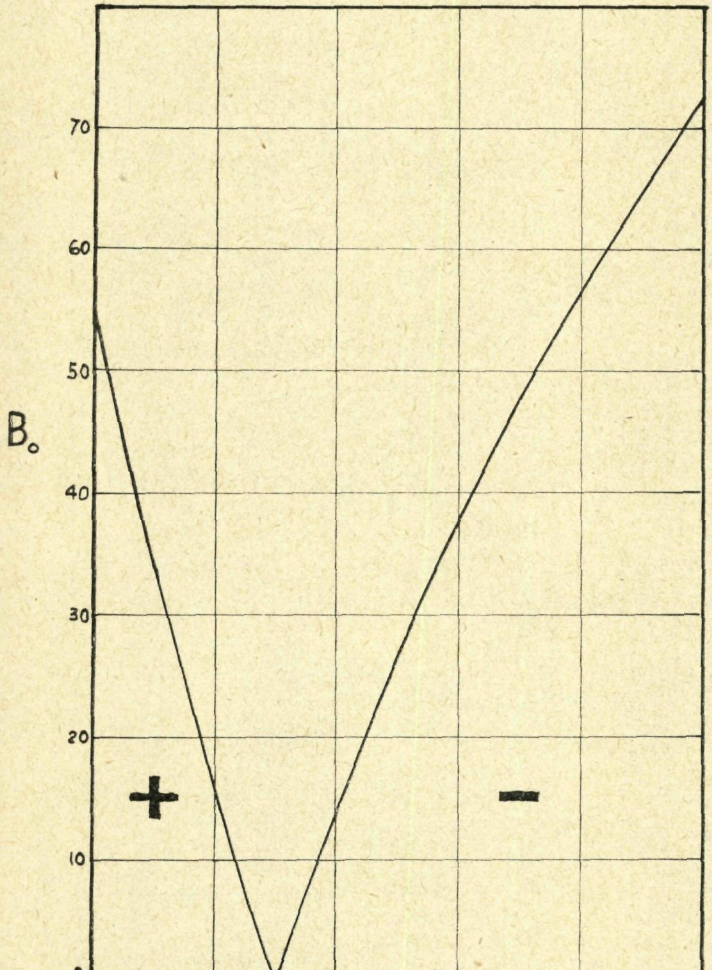

FIG 2

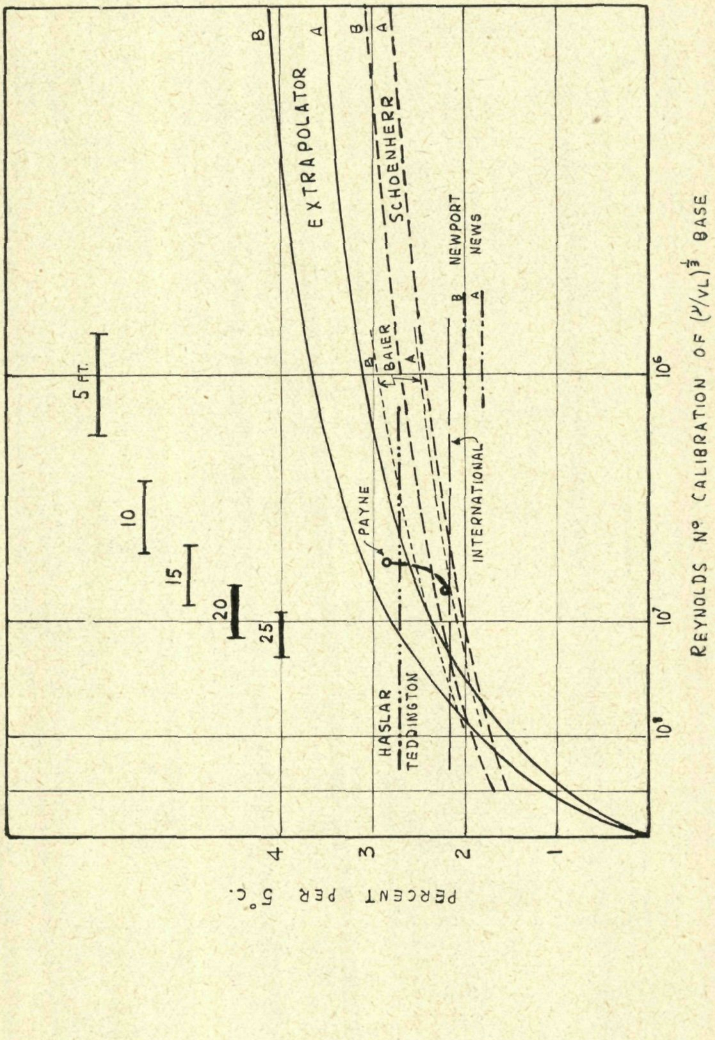
EXTRAPOLATOR
SCHOENHERR
NEWPORT NEWS
BAIER
PAYNE
INTERNATIONAL
HASLAR
TEDDINGTON
5 FT.
10
15
20
25
A
B
4
3
2
1
10^6
10^7
10^8
PERCENT PER 5°C.
REYNOLDS N° CALIBRATION OF $(\nu/VL)^{\frac{1}{3}}$ BASE

Table I.

Temp.	10^2 v in cm²/sec				
	0	.2	.4	.6	.8
0	1.792	1.780	1.768	1.755	1.743
1	1.731	1.719	1.708	1.696	1.685
2	1.673	1.662	1.651	1.641	1.630
3	1.619	1.609	1.598	1.588	1.577
4	1.567	1.557	1.548	1.538	1.529
5	1.519	1.510	1.501	1.491	1.482
6	1.473	1.464	1.455	1.446	1.437
7	1.428	1.420	1.411	1.403	1.394
8	1.386	1.378	1.370	1.362	1.354
9	1.346	1.338	1.331	1.323	1.316
10	1.308	1.301	1.293	1.286	1.278
11	1.271	1.264	1.257	1.251	1.244
12	1.237	1.230	1.224	1.217	1.211
13	1.204	1.198	1.191	1.185	1.178
14	1.172	1.166	1.159	1.153	1.147
15	1.141	1.135	1.129	1.124	1.118
16	1.112	1.106	1.101	1.100	1.090
17	1.084	1.079	1.073	1.068	1.062
18	1.057	1.052	1.047	1.042	1.037
19	1.032	1.027	1.022	1.017	1.012
20	1.007	1.002	.997	.993	.988
21	0.983	.978	.974	.969	.965
22	0.960	.956	.951	.947	.942
23	0.938	.934	.930	.925	.921
24	0.917	.913	.909	.905	.901
25	0.897	.893	.889	.885	.881

Temp.	10^2 v in cm²/sec				
	0	.2	.4	.6	.8
26	.877	.873	.869	.866	.862
27	.858	.854	.850	.847	.843
28	.839	.835	.832	.828	.825
29	.821	.818	.814	.811	.807
30	.804	.801	.798	.794	.791
31	.788	.785	.782	.778	.775
32	.772	.769	.766	.762	.759
33	.756	.753	.750	.747	.744
34	.741	.738	.735	.733	.730
35	.727	.724	.721	.719	.716
36	.713	.710	.708	.705	.703
37	.700	.697	.694	.692	.689
38	.686	.683	.681	.678	.676
39	.673	.671	.668	.666	.663
40	.661	.659	.656	.654	.651
41	.649	.647	.644	.642	.639
42	.637	.635	.633	.631	.629
43	.627	.625	.623	.620	.618
44	.616	.614	.612	.609	.607
45	.605	.603	.601	.598	.596
46	.594	.592	.590	.588	.586
47	.584	.582	.580	.578	.576
48	.574	.572	.570	.569	.567
49	.565	.563	.561	.560	.558
50	.556				

Table II.

C°	0	1	2	3	4	5	6	7	8	9
0	55.08	50.66	46.24	42.16	38.08	34.00	30.26	26.52	22.78	19.38
10	15.98	12.58	9.18	6.12	3.06	+/−	2.89	5.75	8.57	11.19
20	13.87	16.49	19.18	21.49	23.90	26.21	28.56	30.80	33.12	35.33
30	37.43	39.47	41.55	43.59	45.56	47.43	49.33	51.10	53.04	54.88
40	56.58	58.31	60.04	61.57	63.14	64.80	66.47	68.03	69.60	71.03