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A Turbulent Skin-friction Law for Use at Subsonic and Transonic Speeds

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SUMMARY

A proposal is made for a skin-friction law suitable for use in two-dimensional flow at Mach numbers up to about unity. In incompressible flow the law reduces to a slightly modified form of that suggested. by Nash[1]. Compressibility effects are taken into account on the lines indicated by Spalding and Chi[2].

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List of Symbols

x, y	co-ordinates measured along and normal to the surface, respectively
u	mean velocity in x-direction
M	Mach number
ρ	density
ν	kinematic viscosity
T	static temperature
δ	boundary-layer thickness (equation (13))
δ^*	displacement thickness:- $\delta^* = \int_0^\infty \left(1 - \frac{\rho u}{\rho_e u_e^2} \right) dy$
θ	momentum thickness:- $\theta = \int_0^\infty \frac{\rho u}{\rho_e u_e} \left(1 - \frac{u}{u_e} \right) dy$
H	shape factor:- $H = \delta^*/\theta$
G	shape factor:- $G = \frac{1}{u_\tau} \cdot \frac{\int_0^\infty (u_e-u)^2 \, dy}{\int_0^\infty (u_e-u) \, dy}$ in incompressible flow:- $G = \frac{u_e}{u_\tau} \left(1 - \frac{1}{H} \right)$
τ_w	wall shear stress
u_τ	"friction velocity":- $u_\tau^2 = \tau_w/\rho_e$
u_β	velocity appearing in equation (13)
κ	constant appearing in equation (13)

A, B	constants appearing in equation (1) (see also equation (3))
K	function of G appearing in equation (1)

Subscript

e	value at edge of boundary layer

Note

The symbol f( ) denotes any arbitrary function.

1. Introduction

The requirement for a reliable skin-friction law for use at subsonic and transonic speeds has arisen in connection with calculations of the turbulent boundary-layer growth on two-dimensional aerofoils.

The present suggestions are based on the first author's work in Ref. 1, and on the work of Spalding and Chi² which latter related only to the constant-pressure case. The usual assumptions are implicit?, namely, that

(a) the law of the wall is valid

(b) the mean velocity profiles form a two-parameter family.

The law would be expected to fail in strong negative pressure gradients and also close to separation. Nevertheless the aim has been (as in Ref. 1) to ensure an extrapolation to physically plausible values of skin-friction near separation. The effects of surface roughness and transpiration are not considered; nor are the effects of heat transfer.

2. The Skin-Friction Law in Incompressible Flow

For incompressible flow the proposed skin-friction law is of the form

$$\frac{\tau_w}{\rho u_e^2} = \left\{A \,\ell n\left(\frac{u_e\theta}{\nu}\right) + B + K(G)\right\}^{-2}, \qquad \ldots(1)$$

where G is the shape factor based on the velocity defect profile and the other symbols have their usual meanings (see list at the beginning of this paper). Again for incompressible flow, G can be related to H and the wall shear stress by

$$G = \left(\frac{\rho u_e^2}{\tau_w}\right)^{\frac{1}{2}} \left(1 - \frac{1}{H}\right). \qquad \ldots(2)$$

Equation (1) is a slightly modified form of the law derived in Ref. 1. It was decided to base the "flat plate" part of the expression (i.e., with K = 0) on $u_e\theta/\nu$ rather than $u_e\delta^*/\nu$ after making comparisons with the widely used

flat-plate/

flat-plate skin-friction law of Spalding and Chi[2]. The values of $\{\tau_w/(\rho u_e^2)\}^{-\frac{1}{2}}$ predicted by their method vary almost linearly with $\ell n(u_e\theta/\nu)$, and taking

$$\left.\begin{aligned} A &= 2{\cdot}4711 \\ B &= 4{\cdot}75, \end{aligned}\right\} \qquad \ldots(3)$$

equation (1) (with K = 0) represents an empirical fit to their values which is accurate to better than ± 1 percent over a range of Reynolds number $(u_e\theta/\nu)$ from 140 to 10^7 (see Table 1).

Following the approach indicated in Ref. 1 the function K(G) in equation (1) is derived empirically. Equation (1), with the values of A and B quoted above, is used as a basis for correlating skin-friction measurements and a plot of K against G, corresponding to Fig. 2 of Ref. 1, is presented in Fig. 1 of the present paper. The collapse of the' points is within about ± 10 percent of the value of $\tau_w/(\rho u_e^2)$. An empirical fit to the data in Fig. 1, which also satisfies the requirements:-

(a) K = 0 when G = 6·5 (the flat-plate case),

(b) $(dK/dG) \to 1{\cdot}5$ for $G \to \infty$

is given by

$$K = 1{\cdot}5G + \frac{1724}{G^2 + 200} - 16{\cdot}87. \qquad \ldots(4)$$

The specification of the value of $(dK/dG)_{G\to\infty}$ in (b), above, leads to a value of H = 3 at separation (see Ref. 1).

3. Compressibility Effects

The extension, to compressible flow, of the skin-friction law for the constant-pressure case, is straightforward. Spalding and Chi[2] have suggested that if

$$\frac{\tau_w}{\rho u_e^2} = f\left(\frac{u_e\theta}{\nu}\right) \qquad \ldots(5)$$

represents a flat-plate skin-friction law in incompressible flow, a valid relation for compressible flow is given by

$$F_c \cdot \frac{\tau_w}{\rho_e u_e^2} = f\left(F_R \cdot \frac{u_e\theta}{\nu_e}\right), \qquad \ldots(6)$$

where F_c and F_R are both functions of Mach number and wall temperature. For zero heat transfer the following empirical expressions represent the

dependence/

dependence of F_c and F_R on Mach number, and apply for values of M_e up to about 2:-

$$F_c = 1 + 0{\cdot}066\, M_e^2 - 0{\cdot}008\, M_e^3 \qquad\qquad \ldots(7)$$
$$F_R = 1 - 0{\cdot}134\, M_e^2 + 0{\cdot}027\, M_e^3$$

Equations (1), (6) and (7) specify the skin-friction law for a constant-pressure boundary layer (K = 0). There are insufficient data to assess the effect of Mach number on the function K(G) and some provisional assumption must therefore be made to enable calculations to be performed.

Two plausible suggestions can be made. Equation (6) can be generalised to

$$F_c \cdot \frac{\tau_w}{\rho_e u_e^2} = f\left(F_R \cdot \frac{u_e \theta}{\nu}, G \right), \qquad \ldots(8)$$

which implies a law of the form*

$$\frac{\tau_w}{\rho_e u_e^2} = \frac{1}{F_c}\left[A\,\ln\left(F_R \cdot \frac{u_e\theta}{\nu_e} \right) + B + K(G) \right]^{-2}, \qquad \ldots(9)$$

with a suitable definition for G in compressible flow. Alternatively, equation (9) can be modified to

$$\frac{\tau_w}{\rho_e u_e^2} = \left[F_c^{\frac{1}{2}} \left\{ A\,\ln\left(F_R \cdot \frac{u_e\theta}{\nu} \right) + B \right\} + K(G) \right]^{-2}. \qquad \ldots(10)$$

The uncertainty as to whether the function K should (equation (9)) or should not (equation (10)) be multiplied by $F_c^{\frac{1}{2}}$ (or whether neither approach is adequate) can only be resolved by experiment. Nevertheless it will be shown later that equation (10) gives a plausible variation of $\tau_w/(\rho_e u_e^2)$ with H near separation. At a Mach number, M_e, of 1 equations (9) and (10) give virtually the same wall shear stress for values of G up to 20.

4. Relation between G and H in Compressible Flow

The shape factor G can be carried over conveniently into compressible flow if we retain its definition in terms of the velocity defect profile:-

$$G = \frac{1}{u_\tau} \frac{\int_0^\infty (u_e - u)^2\,dy}{\int_0^\infty (u_e - u)\,dy}, \qquad \ldots(11)$$

the/

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* This form of the skin-friction law was used for the calculations of Ref. 3.

the only ambiguity arises in connection with the density appearing in u_τ. It would probably be correct to take some mean density for the outer layer but in the present work we have used ρ_e. The variations in density are, in any case, not large up to $M_e = 1$.

Some assumption about the velocity profiles is required in order to relate G to H since the simple relation

$$G = \frac{u_e}{u_\tau}\left(1 - \frac{1}{H}\right) \qquad \ldots(12)$$

is valid only in incompressible flow. Some calculations have been done using Coles' family of profiles[4] with the wake function approximated by a cosine:-

$$u = \frac{u_\tau}{\kappa}\,\ell n\,\frac{Y}{\delta} + u_e - \frac{u_\beta}{2}\left(1 + \cos \pi\,\frac{y}{\delta}\right). \qquad \ldots(13)$$

The value of κ was taken as 0·41 over the range of Mach numbers considered. The velocity u_β can be related to u_τ and G, by performing the integrations in equation (11) (numerically), and thus to G, M_e and $u_e\theta/\nu_e$ using the skin-friction law (equation (10) was used). The following relation was assumed to exist between ρ and u in the boundary layer:-

$$\frac{\rho}{\rho_e} = \left\{1 + 0{\cdot}178\,M_e^2\left(1 - \frac{u^2}{u_e^2}\right)\right\}^{-1}. \qquad \ldots(14)$$

Equation (14) implies a recovery factor of 0·89.

The results of these calculations are illustrated in Fig. 2. It is found. that the values of H are given to a good approximation by

$$H = (\bar{H} + 1)(1 + 0{\cdot}178\,M_e^2) - 1, \qquad \ldots(15)$$

with

$$\bar{H} = \left(1 - G\,\frac{u_\tau}{u_e}\right)^{-1}, \qquad \ldots(16)$$

except at $M_e = 1$ for the larger values of H where there is a deviation of up to 2 percent in H. Equations (12), (15) and (16) are, of course, consistent at $M_e = 0$.

In the present work we have assumed that equations (15) and (16) are valid up to separation over the range of Mach numbers of interest. on this basis, the skin-friction law is of the form shown in Fig. 3. The differences between equations (9) and (10) are only significant at these Mach numbers for values of G greater than 20. On balance we favour equation (10) because it implies a more plausible variation of H at separation with Mach number; it must be pointed out however that we can offer no experimental justification for this choice.

Tabulated/

Tabulated values of $\tau_w/(\frac{1}{2}\rho_e u_e^2)$ and H for Mach numbers of 0, 0·5 and 1·0, based on equation (10), are presented in Table 2.

5. Conclusions

A skin-friction law suitable for use in two-dimensional turbulent boundary-layer calculations has been constructed on the basis of the work of Nash[1] and Spalding and Chi[2]. The law should be valid. for Mach numbers up to and slightly exceeding unity, and applies to adiabatic smooth walls.

The skin-friction law is specified by:-

$$\frac{\tau_w}{\rho_e u_e^2} = \left[F_c^{\frac{1}{2}} \left\{ 2{\cdot}4711 \, \ell n \left(F_R \cdot \frac{u_e \theta}{\nu_e} \right) + 4{\cdot}75 \right\} + 1{\cdot}5G + \frac{1724}{G^2 + 200} - 16{\cdot}87 \right]^{-2} ,$$

where F_c and F_R are functions of Mach number (see equations (7)). The shape factor G can be related to the ratio, H, of displacement to momentum thickness by:-

$$H = (\bar{H} + 1)(1 + 0.178\, M_e^2) - 1,$$

where

$$\bar{H} = \left\{ 1 - G \left(\frac{\tau_w}{\rho_e u_e^2} \right)^{\frac{1}{2}} \right\}^{-1} .$$

Experimental data are urgently required to check the assumptions, regarding the effects of compressibility under conditions removed from the flat-plate case.

Table 1/

Table 1

Incompressible Flat-Plate Skin Friction

$\frac{u\theta}{\nu}$	$\frac{uL}{\nu}$ *	$\tau_w/(\frac{1}{2}\rho u_e^2)$:- Spalding and Chi	Eq. (1)	Difference (percent)
140'4	2·796 x 10^4	0·0070	0·00695	-0·78
177·6	3·901 x 10^4	0.0065	0·00649	-0·09
233·0	5'679 x 10^4	0·0060	0·00603	0'42
319'4	8·697 x 10^4	0'0055	0·00554	0·73
462'3	1'417 x 10^5	0·0050	0.00504	0' 88
716.0	2·492 x 10^5	0.0045	o-00454	0·84
1208	4·828 x 10^5	0' 0040	0'00403	0·68
2283	1·062 x 10^6	0.0035	0·00351	0.37
5030	2·778 x 10^6	0·0030	0.00300	0.07
1·386 x 10^4	9·340 x 10^6	0·0025	0.00249	-0·24
5·425 x 10^4	4·651 x 10^7	0'0020	0·00199	-0·40
3'955 x 10^5	4'610 x 10^8	0·0015	0~00149	-0·47
1·086 x 10^7	5'758 x 10^{10}	0' 0010	0·000997	-0·30

*L is equivalent run of turbulent boundary layer

Table 2

Table 2

Calculated Values of Skin Friction and H; Me = 0

G	$\frac{u_e\theta}{\nu}$ = 500		= *I d*		= 10^4		= 10^5	
	$\frac{\tau_w}{\frac{1}{2}\rho u_e^2}$ × 10^3	H	$\frac{\tau_w}{\frac{1}{2}\rho u_e^2}$ × 10^3	H	$\frac{\tau_w}{\frac{1}{2}\rho u_e^2}$ × 10^3	H	$\frac{\tau_w}{\frac{1}{2}\rho u_e^2}$ × *Id*	H
5·0	5·908	1.373	4·943	1·331	3·004	1.240	2.016	1.189
5·5	5·555	1.408	4.672	1.362	2.874	1.263	1-945	1.207
6·0	5·237	1·443	4.426	1·393	2.754	1.286	1.878	1.225
6·5	4'949	1·478	4·201	1·424	2·643	1·309	1·815	1·243
7·0	4·685	1.512	3·995	1·455	2·539	1·332	1·755	1.262
7·5	4·444	1·547	3.804	1.486	2·442	1-355	1·699	1.280
8·0	4·221	1· 581	3.627	1·517	2·350	1-378	1.646	1.298
8·5	4·015	1·615	3·462	1·547	2.264	1.400	1·595	1.316
9·0	3·823	1·649	3.308	1·577	2.182	1-423	1.546	1·,334
9·5	3·644	1.682	3·164	1.607	2.104	1-445	1.500	1·352
10	3·477	1·715	3.028	1·637	2.030	1.468	1.455	1.369
11	3·173	1.780	2.780	1·695	1.892	1.511	1·370	1.404
12	2·903	1.842	2.558	1·752	1.766	1-554	1.292	1.439
13	2·662	1.902	2·358	1.806	1.650	1·596	1.219	1·473
14	2·447	I.960	2.178	1·859	1·544	1·637	1.151	1.506
15	2·253	2.014	2.015	1·909	1·445	1·676	1·087	1·538
16	2·080	2·065	1·867	1·956	1·355	1·714	1-028	1·569
17	1.922	2.114	1-732	2.001	1·271	1·750	0.972	1·599
18	1·779	2·159	1.610	2·044	1·194	1·785	0·920	1·629
19	1·650	2·202	1·499	2·084	1·122	1-818	0·872	1·657
20	1-534	2.241	1·398	2·122	1-056	1·851	0-826	1·685
25	1·090	2·402	1·008	2·279	0·793	1·991	0-640	1·809
30	0·806	2·515	o-754	2·394	0·611	2·103	0·506	1'712
35	0.617	2·595	0.581	2·479	o-483	2.192	0.408	1·999
40	0·485	2·653	0.460	2·544	0·390	2.266	0·335	2·073
45	0·391	2·697	0.373	2·594	0·321	2·327	0·279	2·136
50	0·322	2·732	0·308	2·634	0-269	2·378	0·236	2·191
60	0'228	2·781	o-220	2·695	0·196	2.460	o-175	2·283
70	o-170	2·815	0-164	2·738	0.148	2·523	0·135	2·386
80	0·131	2·839	0·128	2·770	0.117	2·572	o-107	2·414
90	0·104	2.858	0.102	2·794	0·094	2.612	0.087	2.463
100	0.085	2·873	0.083	2.824	o-077	2·659	0.072	2·504

contd./

Table 2 (contd.)

Calculated. Values of Skin Friction and H; M_e = 0·5

G	$\frac{u_e\theta}{\nu_e}$ = 500		= 10^3		= 10^4		= 10^5	
	$\frac{\tau_w}{\frac{1}{2}\rho_e u_e^2}$ × 10^3	H	$\frac{\tau_w}{\frac{1}{2}\rho_e u_e^2}$ × 10^3	H	$\frac{\tau_w}{\frac{1}{2}\rho_e u_e^2}$ × 10^3	H	τ -2x- & P & x Id	H
5·0	5·760	1-472	4·818	1·429	2·924	1·336	1·971	I.283
5·5	5'426	1·508	4· 558	1·461	2·800	1·360	1·893	1·302
6·0	5·113	1-544	4·320	1-493	2.685	1·383	1·828	1·320
6·5	4·835	1.580	4·103	1·525	2·577	1-407	1,768	1·339
7·0	4·581	1·615	3·904	1-557	2·477	1·430	1.711	1·358
7·5	4·347	1-651	3·719	1·588	2·384	1·454	1·657	1·377
8.0	4·131	1.686	3·548	1.620	2·295	1·477	1.605	1·395
8·5	3·932	1.721	3·389	1.651	2.222	1.501	1·556	1·414
9·0	3·746	1·755	3.240	1·682	2·133	1·524	1·509	1·432
9·5	3·572	1·790	3.100	1·713	2·057	1·547	1-464	1·450
10	3·410	1·824	2·968	1·744	1·986	1-570	1·421	1.469
11	3·114	1·890	2·727	1.803	1.852	1.615	1·340	1·505
12	Z-851	1·954	2.511	1.862	1·730	1-659	1·264	1·540
13	2.617	2.016	2.316	1.918	1.618	1.702	1·193	1·575
14	2·407	2·075	2.141	1-972	1·514	1·743	1.102	1·610
15	2.218	2.132	1-982	2.023	1-419	1·784	1·066	1.642
16	2.048	2.185	1-837	2·073	1·331	1.823	1.008	1-674
17	1·894	2·235	1·706	2·119	1·249	1·861	0·954	1·707
18	1·755	2·281	1·587	2·163	1·174	1·897	0·903	1·736
19	1.629	2.326	1·478	2.205	1.104	1·931	0.856	1-765
20	1·514	2·367	1·379	2.244	1·040	1·964	0·812	1·794
25	1·079	2·535	0·996	2.408	0.782	2.110	0.630	1.922
30	0·799	2·653	0.746	2.528	0.601	2.226	0·499	2.029
35	0·612	2·737	o-576	2.617	0.478	2.320	0·403	2.119
40	0·482	2·799	0.459	2.686	0-386	2·397	0·331	2.196
45	o-389	2.846	0·370	2.739	0· 318	2.461	0.277	2.263
50	0.320	2.883	0.306	2.782	0.267	2·515	0.234	2.321
60	0.227	2·936	0.219	2.846	0·194	2.601	o-174	2.416
70	0.169	2·973	0.164	2.892	0.148	2.667	0·134	2·492
80	0.131	3.000	0.127	2·927	0.216	2.719	0.107	2·554
90	0.104	3.020	0.101	2.954	0.094	2.762	0.087	2.606
100	0-085	3·036	0·083	2·975	0·077	2·797	0.072	2·649

contd./

Table 2 (contd.)

Calculated Values of Skin Friction and H; M_e = 1•0

G	$\frac{u_e\theta}{\nu}$ = 500		= Id		= 10^4		= 16	
	$\frac{\tau_w}{\frac{1}{2}\rho_e u_e^2}$ × 10^3	H	$\frac{\tau_w}{\frac{1}{2}\rho_e u_e^2}$ × 10^3	H	$\frac{\tau_w}{\frac{1}{2}\rho_e u_e^2}$ × 10^3	H	$\frac{\tau_w}{\frac{1}{2}\rho_e u_e^2}$ × 10^3	H
5•0	5•386	1•769	4.507	1•722	2•728	1•622	1•823	1•565
5•5	5•079	1•808	4•267	1•757	2•611	1.648	1•761	1•586
6•0	4•800	1•846	4•049	1•792	2.507	1.674	1•704	
6•5	4•546	I •885	3•852	1•826	2•410	1.699	1•649	1•626
7•0	4.314	1•923	3.670	1.861	2.320	1.724	1•598	1.646
7’ 5	4•100	1•962	3•502	1•895	2•235	1•750	1.549	1•667
8’0	3'903	2•000	3'416	1•929	2•154	1•775	1•502	1•687
8• 5	3•719	2•038	3•200	1.963	2.078	1•801	1•458	1•707
9•0	3•548	2.075	3•063	1.996	2.006	1.826	1-415	1-727
9•5	3•388	2.112	2.934	2.030	1•937	1•851	1.374	1•747
10	3•238	2•149	2•813	2•063	1•872	1•875	1•335	1•766
11	,2•964	2.221	2•590	2.128	I.750	1.924	1.261	1•805
12	2•720	2.291	2.390	2.191	1.637	1.972	1.192	1•844
13	2.501	2•358	2•209	2.252	1.534	2.019	1.127	1•882
14	2•304	2•423	2•045	2.311	1•438	2.064	I.066	1•919
15	2•127	2•484	1-896	2.367	1.350	2•108	1•009	1•955
16	1.967,	2•542	1•762	2.421	1•268	2.151	0•956	1•990
17	1•822	2•597	1•638	2.472	1.192	2.192	0.906	2•024
18	1.690	2•649	1•525	2.520	1.122	2.231	0.859	2•057
19	1•571	2•698	1-422	2.566	1•056	2.269	0•815	2.089
20	1•462	2•743	I.308	2.607	0.996	2.305	o-774	2.120
25	1•047	2•931	0.966	2.792	0.753	2•466	0.604	2.261
30	0•779	3•065	0•726	2•936	0•584	2.596	0•480	2.380
35	0•598	3•163	0.563	3.030	0.464	2.701	0•389	2.480
40	0-472	3•236	o-447	3•109	0.376	2.788	0.321	2.567
45	0•382	3•292	0.363	3.172	0.311	2.861	0.269	2.642
50	o-315	3.336	0.300	3.222	0-260	2.923	0.228	2•707
60	0.224	3•401	0.215	3.299	0•191	3.023	0.170	2.816
70	0•167	3•447	0.161	3.355	0.145	3.100	0.132	2•903
80	0•129	3•480	0.126	3.397	0•114	3.161	0.105	2• 975
90	0•103	3•506	0.100	3.430	0.092	3.212	0.085	3•034
100	0•084	3•644	0•082	3.456	0.076	3.253	0.065	3•085

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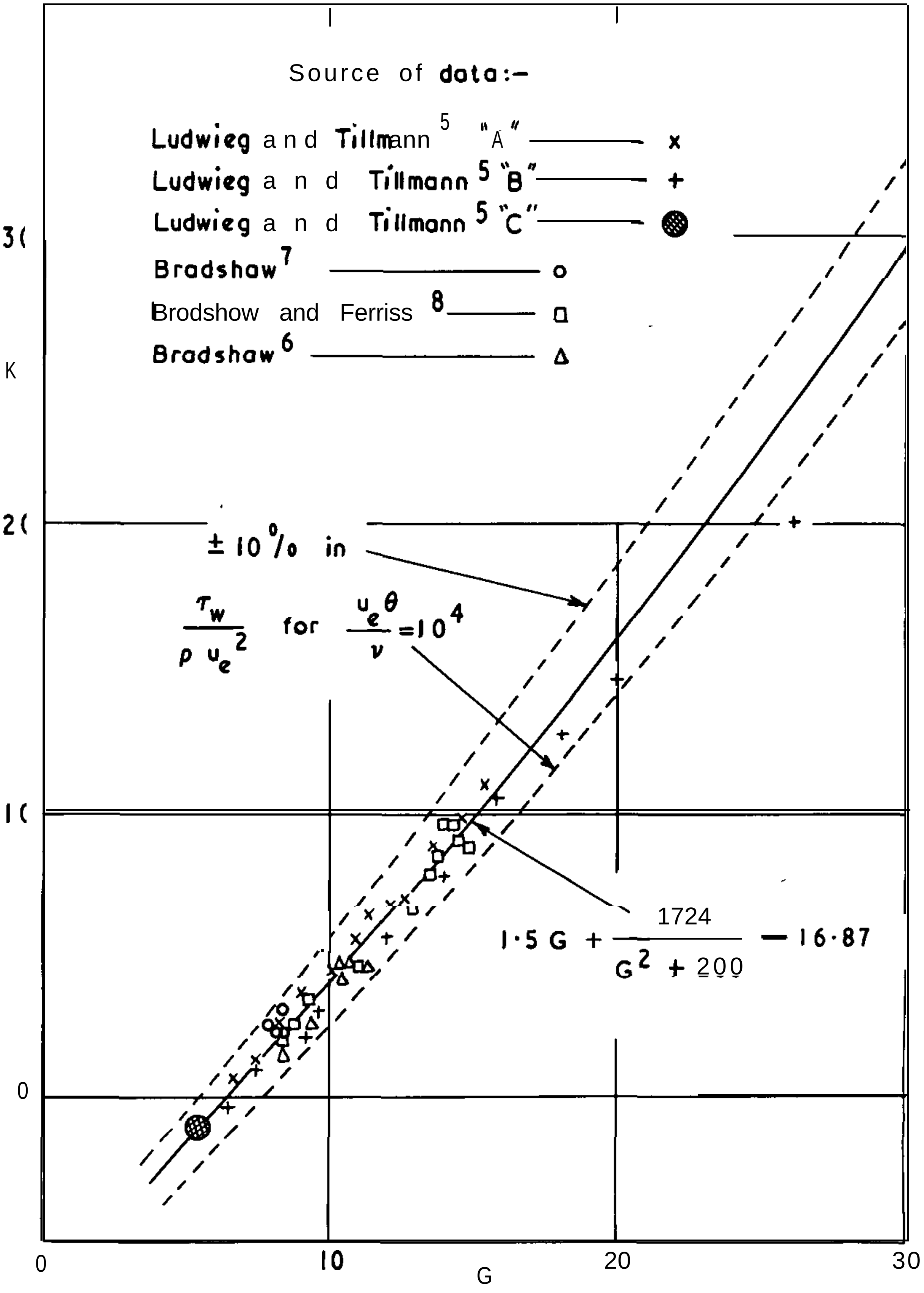
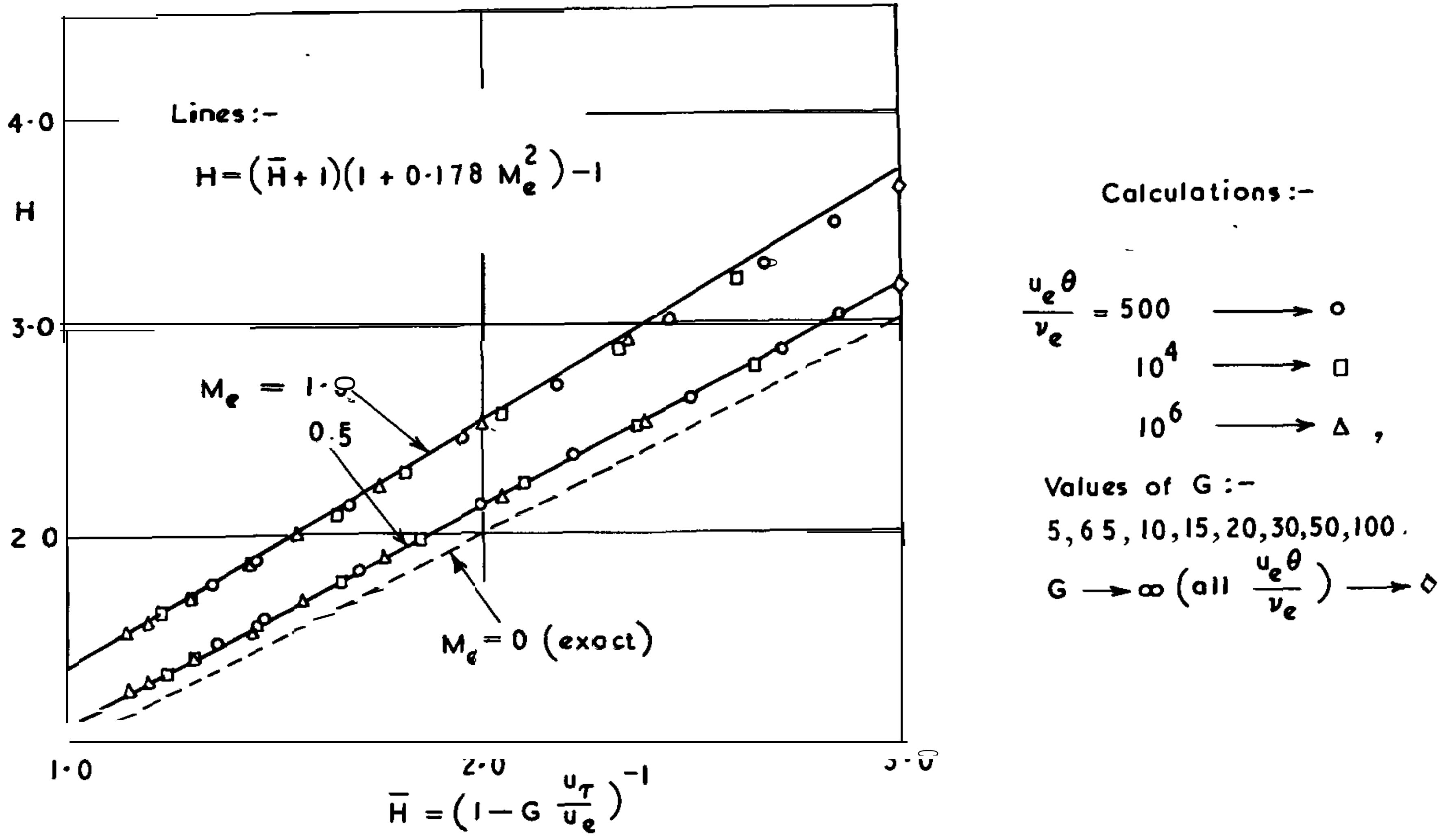
FIG. I



The skin-friction law — correlation of experimental data

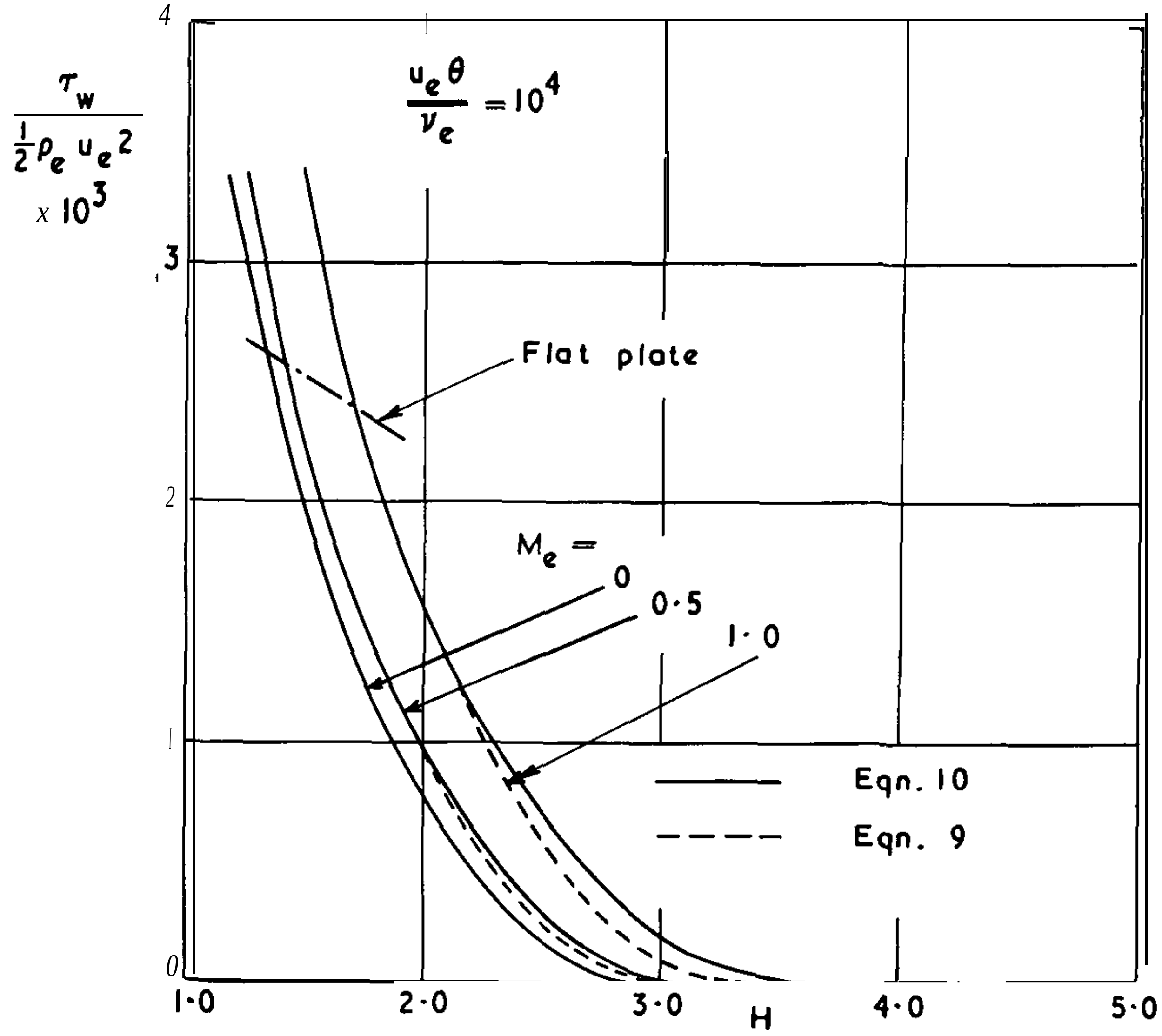
$(M_e = 0)$

FIG. 2



Relation between H, G and wall shear stress in compressible flow

FIG. 3



The skin-friction low: (see olso Table 2)

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