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The aerodynamic resistance of tethered balloons*

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ABSTRACT. Values of the co-efficient of aerodynamic resistance of tethered balloons almost spherical in shape, exposed to the natural wind, are presented. These are compared with the results of experiments on spheres conducted in the laboratory wind channel and in the open air and also with the results of experiments with pilot balloons rising freely in the open or still air. The resistance co-efficient of tethered balloons is found to decrease sharply with increasing Reynolds numbers to a value of about 0·24 at Reynolds number $0\cdot 8 \times 10^5$, then slowly to about 0·075 at Reynolds number $4\cdot 0 \times 10^5$, finally levelling out to a more or less constant value of 0·065 at Reynolds number $5\cdot 0 \times 10^5$ and beyond. The nature of the curve is studied in some detail and possible inaccuracies from excessive air turbulence, lack of sphericity and neglect of effect due to the weight and aerodynamic resistance of the thread are discussed.

1. Introduction

The aerodynamic resistance of spheres at Reynolds numbers which lie beyond the range of validity of the Stokes' law has been investigated upon at various times by different workers using different methods. Among the early workers who utilised the laboratory wind channel for the purpose were Eiffel (1912), Maurain (1913), Prandtl (1914), Constanzi (1914), Loukianof (1914), Riabouchinsky (1914), Pannell (1916) and others. All these workers employed special balances to measure the force exerted on the model by the wind at various Reynolds numbers. One of the most remarkable observations of these early laboratory experiments was that (depending upon the state of turbulence of the airflow approaching the model) there occurred a critical value of the Reynolds number beyond which the co-efficient of the aerodynamic resistance decreased rapidly.

Experiments were also conducted with spheres moving through the natural air. The earliest in this field was Shakespear (1913) who measured the resistance offered by air to the free fall of small celluloid spheres released from high towers. The diameter of the largest sphere used by him was 7·5 cm. Shakespear's experiments were conducted in a range of very low Reynolds numbers and he found that in this range the co-efficient of aerodynamic resistance increased with Reynolds numbers. Pannell (1916) carried out experiments in natural wind with a wooden ball of diameter 0·5 ft and measured the force on the sphere by using a specially constructed balance.

Richardson (1924) measured the aerodynamic resistance of small steel spheres by shooting them upward from a gun at a slight tilt from the vertical in order that a measured wind distribution might bring it back to the gun. Lunnon (1926) used accurate steel spheres and dropped them in air down coal mines.

A group of workers (Cave and Dines 1919, Brazier 1921, Horiguti 1923, and others) carried out experiments on India-rubber pilot balloons rising freely in still or open air. The effect of air resistance on the rate of ascent of these balloons was measured. It was found as a result of these experiments that the co-efficients of aerodynamic resistance of balloons rising in the air were markedly higher than those obtained in laboratory channels for spheres throughout the entire range of Reynolds numbers in

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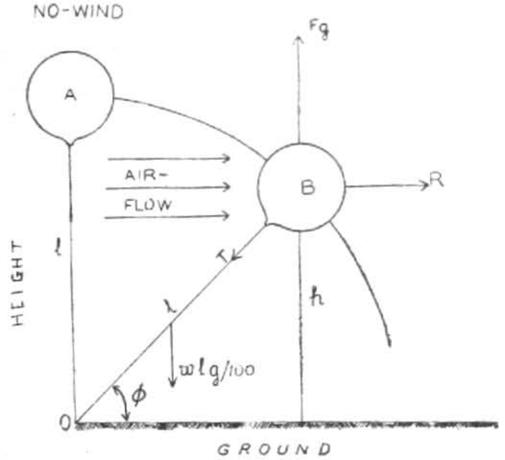

Fig. 1. Deflection of an inflated tethered balloon by the wind

A—No wind position
B—Deflected position

which the balloon experiments were carried out.

In the present paper a method is described in which inflated balloons are exposed to the natural wind at a few feet above the ground by a tethering thread and measurements are made on the deflection of the balloon which is directly proportional to the aerodynamic resistance. Following Bairstow (1913), the results are presented in the form of a curve between the co-efficient of aerodynamic resistance and the Reynolds number. The experimental curve is compared with the pioneer curve of Bairstow who used the experimental results of Eiffel and Shakespear, the mean wind-channel and open-air curve presented by Pannell, and the pilot balloon curve plotted with the results of Brazier, Horiguti, and others.

2. Theory of the present method

A tethered balloon when exposed to the wind at some height above the ground is deflected away from the vertical position by an angle which is proportional to its aerodynamic resistance. It moves along an arc of a circle with the tethering thread as the radius. In the steady state the balloon has a shape which is approximately spherical. The actual shape depends upon the strength of the wind and the angle of deflection from the vertical. But an average shape of the balloon may be described as somewhat conical at the bottom and hemispherical at the top. The phenomenon is illustrated in Fig. 1. If in the deflected position the wind is assumed to act horizontally on the balloon and if F be the free lift of the balloon in gm, acting vertically upward, R the aerodynamic resistance, T the tension on the thread, w the mass per 100 feet of a uniform thread of length l, g the acceleration due to gravity, and ϕ the angle of altitude, it follows, by taking moments of the forces about O along the horizontal and vertical axes, that

$$R = (F - wl/200)\, g/\tan\phi \qquad (1)$$

In the derivation of equation (1), the aerodynamic resistance of the supporting thread itself, assumed to be small, has been neglected. Now, dimensional considerations show that R has to be generally expressed in the following form (Lamb 1932, Shaw 1942).

$$R = \rho L^2 V^2 f(LV/\nu) \qquad (2)$$

where ρ is the air density, L is a linear dimension of the body, V the wind speed, ν the co-efficient of kinematic viscosity, and f a function of the Reynolds number LV/ν and $f(LV/\nu)$ is called the co-efficient of aerodynamic resistance and denoted by k. In the case of a body closely approximating to a sphere as in the present experiment, L may be replaced by the diameter of the balloon d and L^2 by d^2 which is a measure of the cross-section of the balloon presented to the wind. Substitution of the expression (2) for R as applicable to a sphere in equation (1), yields the equation

$$f(Vd/\nu) = (F - wl/200)\, g/\rho V^2 d^2 \tan\phi \qquad (3)$$

Equation (3) gives an expression for the resistance co-efficient k in terms of measureable parameters and some constants. The value of $wl/200$ is only a very small fraction of that of F. For example, in an actual experiment if F is 750 gm, w 20 gm,

TABLE 1

Particulars of balloon and thread used in different ranges of wind speeds

Approximate wind range	Balloon				Thread		
(mph)	Type	Mean weight (gm)	Free-lift (gm)	Diameter (cm)	Description	Thickness (mm)	Weight (gm)
0—5	NR-15	10	18	35·0	3-ply, Office thread	0·33	2·5
0—10	NR-27	23	50	50·0	2-ply, D.M.C. thread	0·43	3·5
0—20	NR-27	23	150	68·0	3-ply, Nylon thread	0·74	12
0—25	NR-70	75	340	89·8	3-ply, Nylon thread	0·74	12
6—30	NR-70	75	500	99·4	Braided Plaited cord (Belfast)	0·94	20
6—35	NR-70	75	750	113·2	Braided Plaited cord (Belfast)	0·94	20

NR—Nagpur Rubber

and l 100 ft, the value of $wl/200$ is only 1·3 per cent of F. As a first approximation, equation (3) may therefore, be expressed in the simplified form—

$$k = f\,(Vd/\nu) = Fg/\rho d^2V^2 \ \tan\phi \qquad (4)$$

Balloons of given diameter and free-lift may be exposed to measurable winds in the manner described in the present method to give corresponding values of ϕ. Results of computation of data thus obtained may be expressed in the form of a relation between the resistance co-efficient k and the Reynolds number Vd/ν as originally suggested by Rayleigh.

3. Experimental arrangement

Balloons and threads used in the present experiments in different ranges of wind speeds are listed in Table 1. For a satisfactory application of the theory, it was necessary to ensure that (*a*) the balloon used for the flights was as truly spherical in shape as could be had under practical conditions and that (*b*) there was little sag in the thread when tethering the balloon. Experience showed that the balloons manufactured by the Nagpur Rubber Factory in India for the pilot balloon work of the India Meteorological Department were *fairly satisfactory in this respect*. For example, an actual measurement of the circumference of an NR-70 balloon with free-lift 750 gm in different orientations through the centre yielded the following readings—

354.3, 354.1, 354.1, 354.1, 354.8 and 353.8 cm.

It will be seen that the imperfection from sphericity amounted to hardly 0·3 per cent on the circumference. To avoid undesirable sag in the thread when supporting the balloon in different wind conditions great care had to be exercised in the proper selection of the thread. Two important qualities were to be ensured, *viz.*, thinness and strength. It must be thin and light in order that it might not have undue pulling-down effect on the balloon and produce a sag and at the same time it must be strong enough to support the balloon under varying wind conditions without breaking off. The threads which were found suitable as a result of experience and which were used are listed in Table 1.

To carry out an experiment, a selected balloon was filled with hydrogen from compressed cylinders to yield a desired free-lift and flown by means of an appropriate length of a chosen thread from a point on the ground to attain a steady stage either at the anemometer height of 33 ft or at the height of a down-wind moving smoke column released from a smoke candle. The angle of altitude of the balloon was measured with the help of an angle-card which was simply a plain

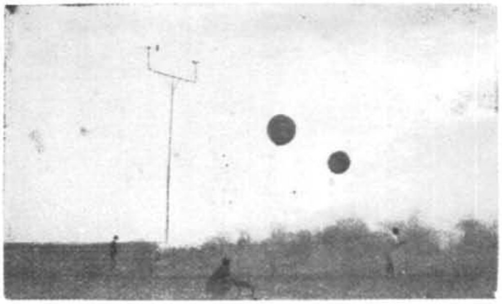

Fig. 2. Photograph of an experiment with two tethered balloons (free lift 50 and 150 gm) exposed to light wind

cardboard, about 8″×10″ in size, on which a sheet of paper with angles graduated on it from 0° to 90° at intervals of 5° was pasted. The angle-card was placed edge-on in a vertical position in the direction of the wind on a short stool or table and the angle of altitude of the balloon above the horizon was measured. The technique of measuring the wind was different in different ranges of wind speeds. If the wind was appreciably strong, say, greater than 6 mph, the usual anemometer method was used. Readings were taken with the help of the distant-reading electric cup anemometer and during the experiment the balloon was kept as close to the anemometer as possible so that one might regard the two being affected by the same wind simultaneously. The reading of the angle of altitude was synchronised with the wind measurement as far as practicable. At wind speeds below 6 mph, which were below the range of the electric cup anemometer, other recourses had to be had. In the present experiments, winds lighter than 6 mph were measured by following smoke-puffs emitted by standard smoke candles. Smoke was emitted continuously from a point near the experimental base for a period of about 15 minutes and while the smoke trail crept along the ground or a few feet above the ground, it was possible to follow and find the rate of travel of individual puffs over measured distances downwind. In this way a large number of readings could be taken to find the wind.

Thread length released depended primarily on the speed of the prevailing wind and the free-lift of the balloon. In light winds when the speed was below 6 mph and smoke trail used to measure the wind, l was about 10 or 15 ft. In stronger winds, lengths released were 33, 50 or 100 ft as required, the aim being to get the balloon in the steady state at the height of the anemometer. In an extremely high wind when the balloon was at a low angle of altitude, unless an adequate length of the thread was released there was a risk of explosion of the balloon on impact with the rough ground.

In the measurement of the angle of altitude, the question of steadiness of the balloon was all-important. Not a single occasion was found in the course of the present experiments when the balloon was observed to be absolutely steady. Air turbulence with associated gusts and lulls in quick succession affected the balloon to varying degrees but it was generally observed that the unsteadiness increased with the speed of the wind and the hour of the day. It was also observed that imperfection from sphericity caused a few balloons to roll in natural winds. In all cases of balloon unsteadiness, a mean angle of altitude was read after giving due weightage to the period of stay of the balloon in different positions over the observed range, although such a procedure was often liable to involve considerable error. But this error was inherent in the problem and the concept of a mean wind in a turbulent medium had only to be accepted in a statistical sense.

Fig. 2 shows a photograph of an actual experiment in progress using two balloons of widely differing free-lifts exposed to the same wind. This was an experiment in light wind. The smoke trail for measuring the wind may also be seen.

4. Data and results of the field experiments

Using the method and experimental technique outlined in the foregoing sections, a large number of field observations using balloons of different free lifts and winds at

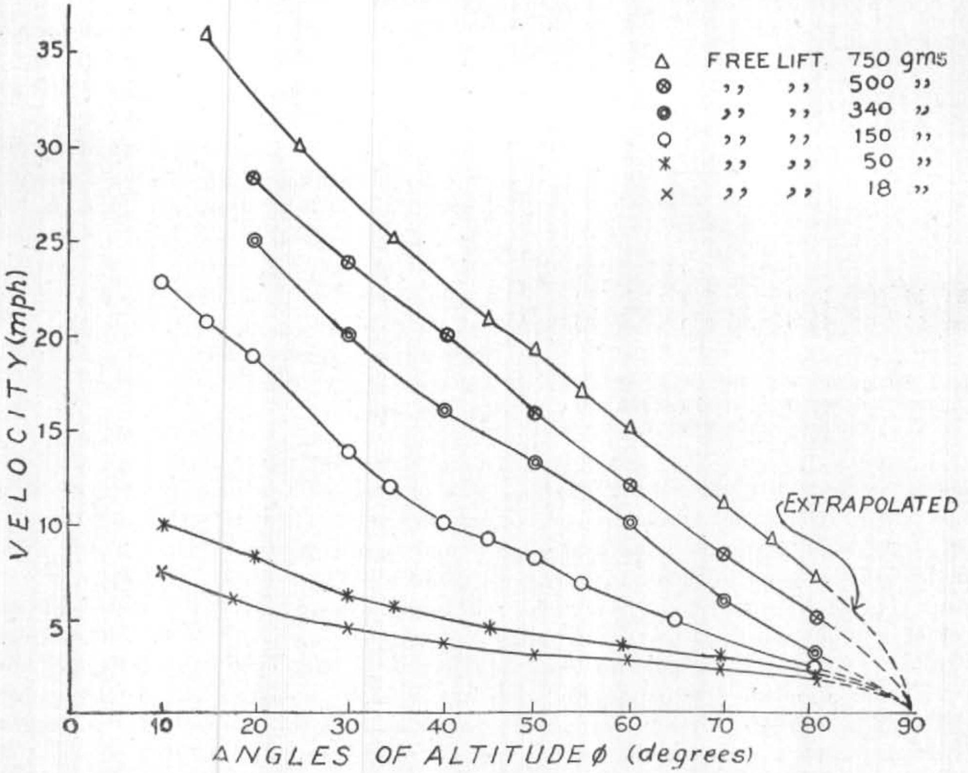

Fig. 3. A chart of wind velocity *vs* angles of altitude in respect of tethered balloons of different free lifts

different speeds were taken during the period from mid-January to about mid-May 1954, over the open plains of Ambala airfield (lat. 30° 56′N, long. 75° 53′ E, height 897 ft a.m.s.l.), India. Observations were taken mostly during hours between 0730 and 1200 IST but some were taken after midday. In Table 2, a collection of these data is presented. Some of the observations were obtained repeatedly on a number of days but only one of these observations is presented to avoid repetition. For example, using a balloon of free-lift 340 gm, an angle of altitude 60° was obtained in a wind 8 mph on as many as five occasions. But the data of only one such occasion is presented. Some of the observations, however, particularly those at wind speeds exceeding 30 mph, could be had only once. In remarks column of Table 2, the balloon steadiness which was a direct measure of the state of turbulence of the atmosphere was expressed in different terms on the basis of the observed fluctuation in the angle of altitude. Thus the balloon was taken as steady when $\delta\phi$ was $<|2\tfrac{1}{2}^\circ|$, slightly turbulent when $|2\tfrac{1}{2}|<\delta\phi<|7\tfrac{1}{2}|$, unsteady or turbulent when $|7\tfrac{1}{2}|<\delta\phi<|15|$, and very turbulent when $\delta\phi>|15|$. In Fig. 3 the mean angles of altitude of the balloon were plotted against the wind velocity in respect of the different balloons used in the present experiment.

The data presented in Table 2 were employed to compute the value of the co-efficient of aerodynamic resistance of a sphere, using equation(4). Among the parameters involved in this equation, F and d were known from measurements on the balloon, g was assumed constant at $979{\cdot}4$ cm sec^{-2} and ρ was taken as the value of air density at temperature and pressure at level of the Stevenson screen. The error involved in using the values

TABLE 2

Record of field observations

Date (1954)	Time (IST)	Free lift (gm)	Length of thread (ft)	Altitude angle (°)	Wind speed near ground (mph)	Wind speed at 33 ft (mph)	Remarks (balloon stability and fluctuations)
Jan 15	0845	340	50	55	—	12·0	Turbulent
,,	1330	340	50	30	—	20·0	Very turbulent
Jan 18	1040	340	33	52½	—	12·5	Turbulent
,,	1220	340	100	20	—	25·0	Very turbulent
Jan 19	1030	340	100	17½	—	27·0	Do.
Jan 24	1050	340	50	45	—	15·0	Turbulent
Jan 30	1150	340	50	60	—	10·0	Slightly turbulent
Feb 13	1130	18	10	80	1·8	—	Steady
Feb 18	0950	18	10	50	3·2	—	Slightly turbulent
,,	0955	150	10	77½	3·1	—	Steady
Feb 24	0835	750	33	70	—	11·0	Slightly turbulent
,,	0902	340	50	50	—	13·0	Unsteady
Feb 25	0755	18	10	45	3·5	—	Steady
Mar 2	1113	750	33	50	—	19·0	Turbulent
,,	1130	500	50	47½	—	17·0	Slightly turbulent
,,	1425	750	50	25	—	30·0	Turbulent
Mar 4	1030	340	50	35	—	19·0	Do.
,,	1325	750	100	15	—	36·0	Unsteady
Mar 5	0845	340	33	55	—	12·0	Slightly turbulent
,,	1003	150	100	15	—	21·0	Turbulent
,,	1005	150	100	22½	—	18·0	Do.
Mar 6	0800	150	10	65	4·9	—	Slightly turbulent
,,	0920	150	50	40	—	10·0	Unsteady
,,	1215	750	33	60	—	15·0	Slightly turbulent
,,	1238	500	50	60	—	12·0	Do.
,,	1315	150	50	35	—	12·0	Unsteady
Mar 8	0940	150	33	55	—	6·5	Slightly turbulent
,,	0945	150	50	45	—	9·0	Do.
Mar 10	0753	150	50	50	—	8·0	Do.
Mar 11	0758	150	50	37½	—	11·0	Do.
,,	0828	500	33	68	—	9·0	Do.
,,	0855	50	50	10	—	10·0	Do.
Mar 12	0800	150	10	80	2·7	—	Steady
Mar 13	0830	150	50	40	—	10·0	Do.
,,	1218	150	100	20	—	19·0	Turbulent
Mar 15	0746	750	33	75	—	9·0	Slightly turbulent
,,	0752	500	33	70	—	8·0	Do.
,,	0800	340	50	65	—	8·0	Do.
Mar 16	0830	50	50	32½	—	6·0	Do.
,,	0835	150	50	53	—	7·0	Do.
,,	0839	750	33	80	—	7·0	Do.
,,	0922	340	33	70	—	6·0	Do.
Mar 17	1310	150	50	30	—	14·0	Turbulent
Mar 18	1028	750	33	58	—	16·0	Do.
,,	1322	340	100	22½	—	23·0	Do.
Mar 27	1327	340	50	40	—	16·0	Do.
Mar 28	0845	500	33	37½	—	13·0	Slightly turbulent

TABLE 2 *(contd)*

Date (1954)	Time (IST)	Free lift (gm)	Length of thread (ft)	Altitude angle (°)	Wind speed near ground (mph)	Wind speed at 33 ft (mph)	Remarks (balloon stability and fluctuations)
Apr 2	0735	18	10	65	2·5	—	Steady
,,	0737	18	10	75	2·0	—	Do.
,,	0739	50	10	78	2·2	—	Do.
,,	0742	50	10	83	2·0	—	Do.
Apr 3	0927	50	10	50	4·3	—	Slightly turbulent
Apr 6	0805	50	10	62½	3·2	—	Do.
Apr 8	0730	18	10	60	2·7	—	Do.
,,	0740	18	10	35	4·0	—	Do.
,,	0750	50	10	70	2·7	—	Do.
,,	0800	50	10	57½	3·5	—	Do.
Apr 9	0720	50	15	65	3·0	—	Steady
,,	0728	18	15	40	3·7	—	Do.
,,	0730	18	15	30	4·4	—	Do.
,,	0732	18	15	25	5·0	—	Do.
,,	0733	18	15	18	6·2	—	Do.
,,	1250	750	100	32½	—	26·0	Very turbulent
Apr 10	0729	18	10	70	2·2	—	Steady
,,	0756	50	50	25	—	7·0	Slightly turbulent
Apr 12	0744	18	10	43½	4·2	—	Steady
,,	0748	18	10	37½	3·9	—	Do.
,,	0751	18	10	22½	5·3	—	Do.
,,	0755	50	10	45	4·6	—	Do.
Apr 14	0945	150	100	17½	—	20·0	Turbulent
,,	0955	150	100	10	—	23·0	Very turbulent
Apr 15	0850	150	50	27½	—	15·0	Slightly turbulent
,,	1250	500	100	20	—	28·0	Very turbulent
Apr 20	0730	50	15	35	5·7	—	Steady
,,	0731	50	15	30	6·2	—	Do.
May 1	0830	340	15	85	2·4	—	Do.
,,	0835	340	15	80	3·2	—	Do.
,,	0840	340	15	83	2·7	—	Do.
,,	0845	340	15	87	2·1	—	Do.
,,	1130	50	50	20	—	8·0	Slightly turbulent
,,	1135	50	100	15	—	9·0	Do.
,,	1145	500	33	80	—	5·0	Do.
,,	1150	500	33	73	—	7·0	Slightly turbulent
,,	1200	500	33	65	—	10·0	Do.
May 3	0822	750	33	72½	—	10·0	Steady
,,	1130	750	50	55	—	17·0	Very trubulent
,,	1135	500	100	45	—	18·0	Do.
May 4	0748	500	50	52½	—	15·0	Turbulent
,,	0754	500	50	50	—	16·0	Do.
,,	0800	500	50	42½	—	19·0	Do.
May 7	1000	500	50	55	—	14·0	Do.
May 8	0730	18	100	10	—	7·5	Slightly turbulent

TABLE 3

Mean monthly temperatures (°C) at heights of 4 and 35 ft above ground over Poona at two temperature epochs (Ramdas)

Time of observation	Height above ground (ft)	Jan	Feb	Mar	Apr	May
Maximum temperature epochs	4	28·4	31·2	32·1	37·9	36·8
	35	26·5	29·8	30·1	35·6	34·5
Minimum temperature epochs	4	10·4	14·5	19·9	22·7	22·7
	35	13·2	16·7	21·5	23·5	23·5

of these elements at the level of the screen instead of at the anemometer height was not likely to be appreciable in view of very small pressure and temperature difference between these levels. The pressure difference may be taken to be about 1 mb and Ramdas (1943) has shown that between the screen height of 4 ft above the ground and height of 33 ft over Poona, the mean temperature difference varied with time of the day and the season but seldom exceeded 2° to 3°C. A relevant extract from his paper is given in Table 3. A reference to Standard Meteorological Tables (Smithsonian 1939) reveals that neglect of a difference of 2° or 3°C at m.s.l. pressure of 1013·2 mb involves an error of even less than 1 per cent in air density. In the present work, mean monthly values of air temperature and pressure at the screen height over Ambala at some set hours of the day were determined during the period of the investigation. These values are graphically shown in Fig. 4 and were used to compute the values of air density using the standard equation

$$\rho = 348.4\,(P - 3e/8)/T$$

where P, e and T are the air pressure (mb), vapour pressure (mb) and air temperature (°A) respectively. The period of the present investigation being the dry period in northern India, the vapour pressure was of a relatively small order compared to air pressure, the value mostly varying between 5 and 10 mb and sometimes going up to about 15 mb when western depressions affected the area. Neglect of such a small value of vapour pressure involved an error of even less than 0·5 per cent in air density. The simplified formula $\rho = 348{\cdot}4\,P/T$ was, therefore, used in the computation. The values of air density thus computed are included in Fig. 4. In the same diagram are also shown the ν—curves, obtained by dividing the values of the co-efficient of dynamic viscosity, as given by Montgomery (1947), by the simultaneous values of air density for the different months of the period of the investigation.

The results of the computation for the co-efficient of aerodynamic resistance are presented graphically in Fig. 5 in which values of $k=R/\rho d^2 V^2$ have been plotted against Reynolds number Vd/ν. The range of Reynolds numbers over which the resistance co-efficient has been found varies from $0{\cdot}2\times10^5$ to $1{\cdot}1\times10^6$. It is found that the values of k are fairly consistent at Reynolds numbers higher than $1{\cdot}0\times10^5$. Excepting a few odd values, the scatter of individual plots about the mean curve is within tolerable limits. But at lower Reynold numbers, k values have large scatter. The general trend of the experimental curve is a rapid decrease of the value of the co-efficient k up to about $0{\cdot}8\times10^5$ Reynolds number after a characteristic inflection in the region of about $0{\cdot}5\times10^5$ Reynolds number, a slow and steady decrease from a value of 0·24 to 0·09 between Reynolds numbers $0{\cdot}8\times10^5$ and $3{\cdot}0\times10^5$ and then a very slow decrease to reach a more or less constant value of 0·065 at Reynolds numbers $5{\cdot}0\times10^5$ and beyond.

5. Discussion

A comparative study of the present experimental curve with those obtained by other

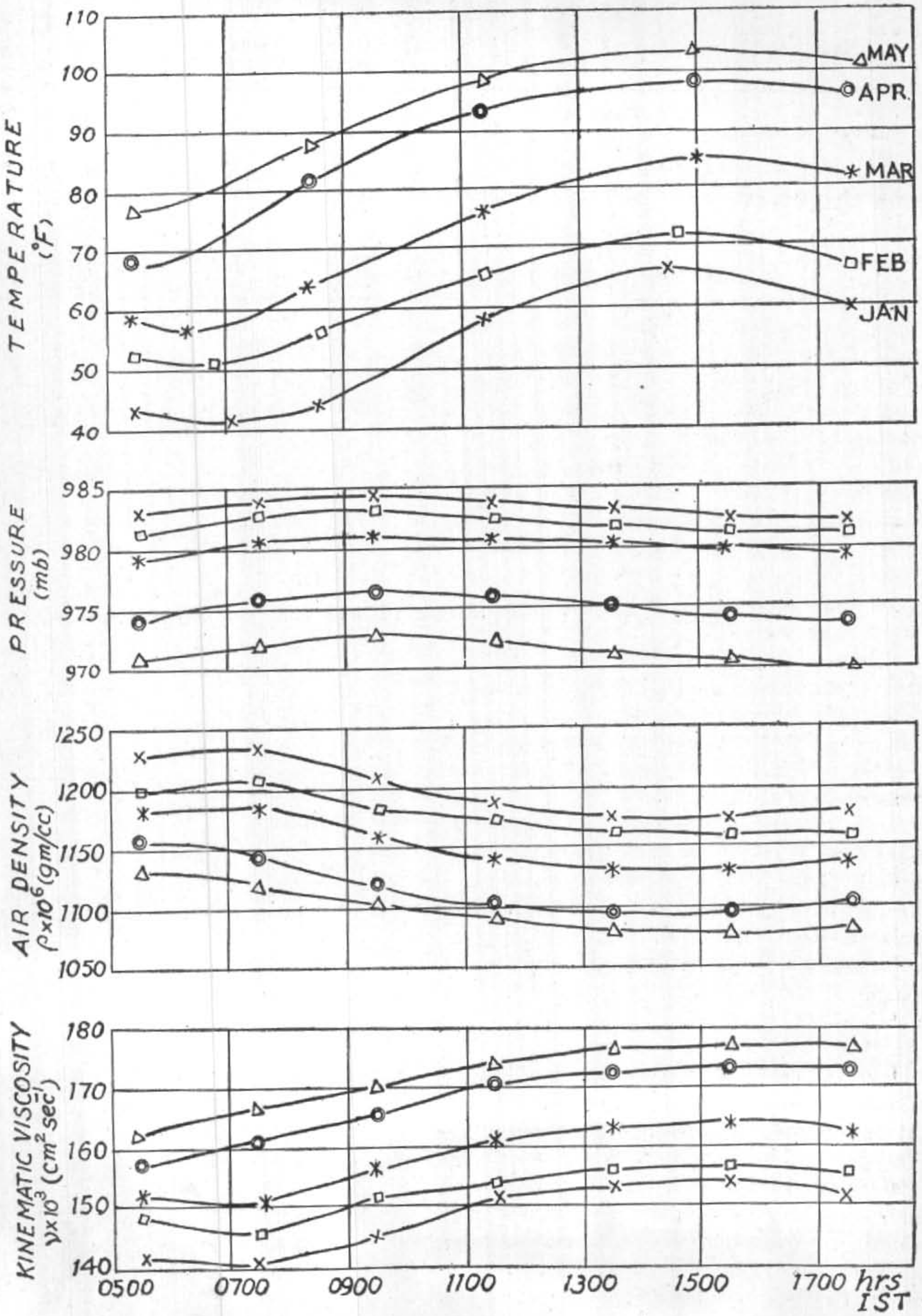

Fig. 4. Diurnal variation of mean monthly temperature, pressure, air density and kinematic viscosity over Ambala, mid-January to mid-May 1954

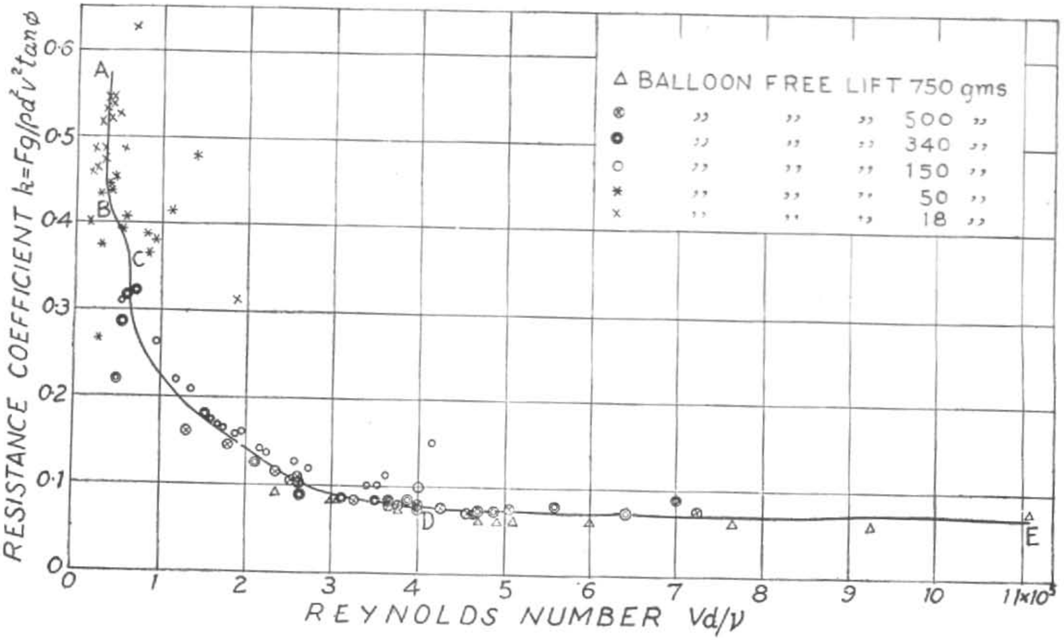

Fig. 5. The co-efficient of aerodynamic resistance of tethered balloons at different Reynolds numbers

workers in this field (Fig. 6) reveals some interesting features of similarity. In all curves in Fig. 6 there is a general decrease of the value of k with increasing Reynolds numbers. But the Reynolds number at which the decrease begins or ends is somewhat different in the different curves. The curve from data of pilot balloon flights shows a more or less uniform decrease of k all through till at Reynolds number about $3 \cdot 0 \times 10^5$ the curve levels out to a constant value of about $0 \cdot 17$. In the curve presented by Pannell for spheres, k after having a precipitous fall at extremely low Reynolds numbers passes through an inflection point at Reynolds number about $0 \cdot 5 \times 10^5$ and then decreases first slowly and then rapidly till at Reynolds number about $2 \cdot 0 \times 10^5$ it attains a value of $0 \cdot 09$ but increases slowly at higher Reynolds number to level out to a value of $0 \cdot 11$ beyond 4×10^5. Bairstow's pioneer curve for spheres shows similar trends except that in it there is an actual increase of k between Reynolds numbers $0 \cdot 2 \times 10^5$ and $0 \cdot 6 \times 10^5$ instead of a point of inflection and once having levelled out to a value of about $0 \cdot 07$ at a Reynolds number about $2 \cdot 5 \times 10^5$ it does not rise again. In the present experimental curve, a weak inflection is noticeable around a Reynolds number $0 \cdot 5 \times 10^5$. The curve otherwise has a steep fall up to Reynolds number about $0 \cdot 8 \times 10^5$, followed by a sliding fall up to about $4 \cdot 0 \times 10^5$ beyond which it approaches a constant value of about $0 \cdot 065$. One of the most noticeable features of the present curve is the wide range of Reynolds numbers it covers, which is nearly three times the range of other curves. The interpretation of the resistance curve found as a result of the present investigation may be sought in the light of current knowledge of the turbulent structure of the natural wind. To this end, let us divide the curve in Fig. 5 into four parts—AB, BC, CD and DE. In the Reynolds number scale, AB is in the region lower than $0 \cdot 4 \times 10^5$, part BC is confined between $0 \cdot 4 \times 10^5$ and $0 \cdot 7 \times 10^5$, CD between $0 \cdot 7 \times 10^5$ and about $4 \cdot 0 \times 10^5$ and part DE extends beyond $4 \cdot 0 \times 10^5$ to higher Reynolds numbers. The most remarkable part in the whole curve is the part BC which would appear to be some kind of a transition between the parts AB and CD. But about its reality there may be some reasonable doubt. Perhaps, with greater amount of data, it may be found non-existent. The part BC may, therefore, be left out of consideration for the present. We may now take the part AC which is characterised by a precipitous decrease of k with increasing Reynolds numbers. This part of the curve probably marks the beginning of a breakdown of the streamline structure of the air flow. At higher Reynolds numbers when we come to consider the part CD, the air flow is increasingly turbulent. As the turbulent energy increases, more and more components of the turbulence spectrum are brought into the field with a consequent loss in aerodynamic resistance. However, as the turbulent energy increases still further, most of the frequency components of the turbulent energy spectrum are fully excited (Saha 1954). When this state is reached there is little further change in the value of the resistance co-efficient. This happens in part DE of the present curve.

In discussing the validity of the results of the present investigation, it would be well to bear in mind two important assumptions which were made in regard to (*a*) flow of air past the balloon only in the horizontal direction and (*b*) the spherical shape of the balloon in all wind speeds. In making assumption (*a*), a severe restriction was laid on the actual turbulent condition in which lateral and vertical components of the turbulent velocity assumed almost as great an importance as the down-wind component. In fact, in the highly turbulent state, the three components are probably equal to each other. Large-scale fluctuations of the angle of altitude in high winds as reported earlier in the paper are probably to be explained by the joint effect of these vertical and lateral as well as down-wind components of turbulent winds. In making the second assumption, some error was involved as the balloon was made of highly elastic rubber and under pressure of the wind some amount of deformation from the spherical shape was always there. But visual observation showed that the extent of deformation produced was not appreciable except at very high Reynolds numbers. No quantitative measurement of deformation produced in any actual case was attempted.

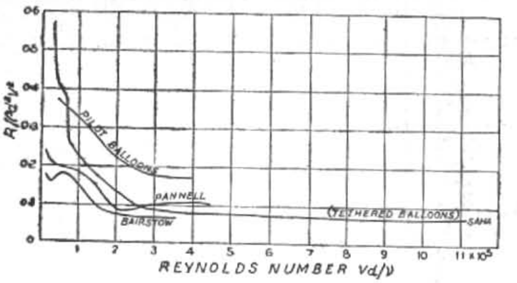

Fig. 6. Comparison of the present experimental curve with those for spheres and freely rising pilot balloons

Further, neglect of the weight of the thread and its aerodynamic resistance involves an error which may be appreciable if the length is not kept short or if a thin or light thread is not used. These forces have a pulling-down effect on the balloon and may also produce perceptible sag. Selection of a proper thread minimises these effects but even with the present threads it may be maintained that the error due to these effects was at a reasonable minimum when the thread length was kept below 100 feet. If the thread be assumed cylindrical in shape and a squared velocity relation is assumed to hold for the aerodynamic resistance of the thread, it may be shown in the case of a braided thread (*vide* Table 1) of average length 50 feet supporting an NR-70 balloon of free-lift 750 gm in a uniform wind of 20 mph blowing across the system of the thread and the balloon on a summer morning, that the combined effect of the weight and the aerodynamic resistance of the thread would lead to an under-reading of the angle of altitude by about $1\frac{1}{2}$ degrees and over-evaluation of the co-efficient of aerodynamic resistance of the balloon by about 5 per cent. In this estimation the sag of the thread has been assumed to be negligible, an assumption which is in close accord with observation.

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