(*Paper No. 1840.*)

**"A Study of the Problem of Aerial Navigation, as affected
by Recent Mechanical Improvements."**

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IN a few remarks appended by the Author¹ of this Paper to the discussion on Mr. Thornycroft's communication "On Torpedo-boats and Light Yachts for High-speed Navigation," he ventured to express the view that the remarkable reduction lately effected in the weight of power-producing apparatus, might have an important influence on the solution of the problem of the navigation of the air. He considers it may not be out of place, as a matter of mechanical investigation, that he should offer to the Institution some account of the facts and reasonings on which this view is founded.

The serious discussion of the possibility of commanding locomotion at will through the air is often avoided from the fear of encountering popular ridicule. But the engineer and the student of mechanical science will know that there is nothing unreasonable or inconsistent with mechanical principles in the idea. The problem of producing motion in a given direction through the air is analogous with that of producing motion in a given direction through the water, and is subject to the same general laws. Hence, as the latter problem has been long ago practically solved, one may fairly inquire how far the former one is likely to admit of solution also.

The complete form of the problem of aerial navigation is, of course, that of flying, and the study of the mechanical conditions of that wonderful process is one of the most interesting offered by nature. But as hitherto no approach has been made to any artificial imitation of it, its discussion would be out of place here; and it is proposed to confine attention to a modified form of the problem, in which one of its chief difficulties has been removed. The invention of the balloon, about a century ago,

¹ *Vide Minutes of Proceedings Inst. C.E., vol. lxvi., p. 174.*

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overcame the great obstacle to aerial operations caused by the action of gravity, and so immensely simplified the conditions to be studied, as to bring the problem much more within the reach of practical skill. It is therefore to aerial navigation by means of balloons that this Paper applies.

The analogy between motion in water and in air has already been pointed out; and it becomes closer when the aeronautic apparatus has the power of floating. Now it is known by every-day experience that if, in the case of a boat or steamer, an action can be applied, by a force within the vessel, against the surrounding water, the reaction will propel the floating body in an opposite direction: and similarly if a force carried in a balloon can be made to act against the surrounding air, it is equally certain that a propulsion in the opposite direction will be given to the balloon.

And it follows that if motion can be given through the air, there will also be a *steering* power; for the well-known contrivance of the rudder will be as effective, if properly proportioned, in the rarer as in the denser medium. Hence a balloon thus constituted will be capable of navigating the air in any required direction, or will be (to borrow a very appropriate term from the French) a *dirigible* balloon.

The problem, then, in regard to such a balloon is, to ascertain by what means an action can be caused against the air by some force within the balloon itself; and to investigate the result of this force in effecting the propulsion.

The discussion of this problem now to be offered is of no speculative character, and contemplates no novelty of invention. It will be based entirely on existing facts, and on trials made on a full practical scale, which will furnish the data for reasoning on the future possibilities of aerial navigation. Hence it is proposed (I.) To state what has been done; (II.) To infer from this what may be done; and (III.) To offer some considerations on the subject of a practical character.

WHAT HAS BEEN DONE.

It is worthy of record that the analogy between water and air navigation was perceived by a great mind, at the time the balloon was invented. As early as December 1783, *i.e.* only six months after Montgolfier's first public experiments, Lavoisier, the most eminent chemist and physicist of the day, gave before the French

Academy¹ an admirable *résumé* of the conditions which should be fulfilled in aerostatic machines, and which are as perfectly applicable now as they were then. In studying the subject he saw clearly that, by reaction against the air, an independent motion might be given to the balloon, and might be made use of to modify the direction impressed upon it by the wind, or in other words to render it dirigible. Accordingly, the last of his conditions ran thus :—

Finally, by employing the force of men, it appears certain that it will be possible to cause the direction of the balloon to vary from the direction of the wind, under an angle of several degrees.

Lavoisier's idea was discussed by the Montgolfiers, who proposed to adapt oars to their balloons; and other early aeronauts from time to time made experiments in the same direction; but none of these efforts were successful. Hence the great expectations which had been raised as to the new power of locomotion gradually dwindled away, and an opinion set in that aerial navigation by balloons was, in the nature of things, impossible. This view prevails widely at the present day, and it is not unusual to see the most preposterous and unmechanical notions gravely put forward in support of it. But the explanation of the failure of the early attempts is obvious enough; it lies simply in the difficulty of finding any adequate means of applying the power. Oars were unsuitable with total immersion, and no mechanical ingenuity could imitate the beautiful action of a fish's fin, or a bird's wing. To make the balloon a manageable locomotive agent required a degree of advancement in mechanical practice which has only been attained in very recent times.

It was not till half a century after the invention of balloons that the introduction of the screw propeller² removed the first difficulty, by providing an efficient apparatus for acting against the air. This apparatus was at once of the simplest character, suitable for total immersion, easily worked, and capable of applying, in the most effectual way, almost any amount of power that could be desired. After its introduction the practicability of aerial navigation could be no longer doubtful.

¹ Reprinted in the "Comptes Rendus," vol. lxxi., p. 608.

² The screw had often been proposed, at earlier times, as a mode of propelling ships, but it was not believed in till the date of Mr. F. P. Smith's successful trial in November 1836. The "Archimedes," the first large screw steamer, put to sea on the 15th May, 1839.

The first person who made a serious attempt to utilise the screw for balloons was a young French engineer whose name has since become famous in the engineering world on other grounds, M. Henry Giffard, the inventor of the "Injector," one of the most elegant contrivances ever introduced into engineering. It was about 1850 that M. Giffard turned his attention to the matter, but he found there was much to be done before the experiment could be carried out with any chance of success. In the first place he saw that the ordinary form of the balloon, namely globular, was very unsuitable when lateral motion through the air had to be effected; the well known analogy of vessels for water-navigation demanding that the shape should be elongated, diminishing at the bow and stern. To complete the analogy, it was also necessary that this elongated vessel should have a keel and a rudder. As a power to work his screw, he took the bold step of using a steam engine, adopting, however, ample precautions against fire, among which was the ingenious expedient of turning the funnel downwards, and producing the draft by a steam blast, as in the railway locomotive.

His balloon was 12 metres diameter and 44 metres long. The car was suspended by a net in the usual way, and there was a large triangular sail attached to the stern, serving as keel and rudder combined. The steam engine was 3 HP., and worked a two-bladed screw 3·4 metres diameter, which could be given one hundred and ten turns per minute. The general appearance of the balloon will be seen from the accompanying figures.

M. Giffard ascended from Paris on the 24th September, 1852. Having arrived at a convenient height, he started his engine, and the independent motion produced thereby became at once evident by the prompt obedience of the balloon to the action of the rudder. It was "under way," and could be steered like a ship at sea. He found that the screw gave an independent velocity through the air of from 2 to 3 metres a second, or $4\frac{1}{2}$ to $6\frac{3}{4}$ miles an hour.¹

He intended to continue his experiments, but he found that, in order to get the best results, many improvements were necessary which would take time. His attention was then occupied on

¹ A description of the balloon and its voyage was published in "La Presse" of the 25th September, and was reprinted eighteen years later in the "Comptes Rendus," vol. lxxi., p. 683. See also "Les Ballons Dirigeables," by Gaston Tissandier. Paris. 1872; from which the figures are borrowed.

other mechanical subjects, but in 1867 and 1868 he had occasion to construct two large captive balloons, in which were perfected

M. H. Giffard's Dirigible Balloon, 1852.

some of the improvements he had in contemplation, in particular the impermeability of the envelope, a more mechanical construction

of the valves, and a better and cheaper mode of preparing pure hydrogen.

During the siege of Paris in 1870, balloons were used to a large extent, as is matter of history, in order to get despatches out of the city. They were, unfortunately, not available for communication in the other direction; but it occurred to the authorities that if they could be given even a slight independent motion they might be made so, and this led to another experiment under the auspices of M. Dupuy de Lôme, the eminent naval architect to the French Government. He constructed a balloon, of an elongated shape, 14·84 metres diameter and 36·12 metres long. The car carried a screw-propeller of two sails, 9 metres diameter, intended to be turned by four men, a relay-gang being also taken up to relieve them. The experiment was interrupted by the Communist insurrection, but it was completed afterwards, and the ascent was made on the 2nd February, 1872. Careful observations were taken during the voyage, and they established beyond a doubt the efficiency of the propelling apparatus in giving a velocity to the balloon independent of the wind. It was found that when all eight men were working together at the screw, giving it $27\frac{1}{2}$ revolutions per minute, an independent velocity was obtained of 2·82 metres per second, or about 6·3 miles per hour.

As a matter of fact M. de Lôme did not accomplish much beyond what M. Giffard had done many years earlier; but his work has a peculiar merit of its own, namely the full and able manner in which, applying to the subject his gréat knowledge of marine navigation, he has discussed all the elements of the problem. And by the lucid detailed descriptions and explanations he has put on record, both of his calculations and of his experimental results, he has given a firm basis for the extension of the principle to a wider range.¹

The importance of these two trials, as bearing on the practicability of aerial navigation, cannot be denied; but doubts have been expressed whether the results given can be implicitly accepted. It is said (1) that the determination of the independent speed must be so difficult as to be liable to error; (2) that the results of the two trials, with such different amounts of power, are very discordant, and (3) that had such marvellous accounts been credited at the time they must have been followed up. In

¹ These particulars will be found in several elaborate articles communicated from time to time to the Academy of Sciences, and published in the "Comptes Rendus," vols. lxxi. and lxxiv.

M. Giffard's case, there is, it is true, only the unsupported statement of an engineer of known reputation and great skill; but with regard to M. de Lôme's trial, a reference to the "Comptes Rendus" will show abundant evidence of the correctness of his statements. He pre-arranged with great care the modes of observation; he was accompanied and assisted by several other persons, and it is incredible that the full detailed particulars communicated to such a body as the French Academy, by a man of such high position, can have been otherwise than trustworthy. The discrepancy between the two trials will be explained elsewhere; and the apparent neglect of the experiment is easily accounted for by the circumstances of the time, and the want of any sufficient inducement for its renewal. The best answer however to these objections is, that the results are perfectly consistent with mechanical principles, as will now be shown.

WHAT MAY BE DONE.

Under this head it is proposed to investigate generally, as a mechanical problem, the capabilities of balloons for aerial navigation.

Assuming that a suitable elongated shape, of circular section, has been determined on, let the maximum diameter be represented by d , and the length by l . Then the contents will be proportional to $d^2 l$, and the *ascending force* of the gas may be expressed by $A d^2 l$; where A is a coefficient depending on the shape of the vessel, and on the specific gravity of the gas compared with that of the surrounding air.

The *weight* of the envelope, assuming the material the same, will vary as the maximum diameter multiplied by the length; and for the sake of simplicity, one may, probably without much error, apply the same proportion to the other parts of the structure generally, apart from the motive power. Therefore, using another coefficient to be obtained from experience, the weight of the structure may be expressed by $B d l$.

Hence the *available ascending power* = $A d^2 l - B d l$, or = $(A d - B) d l$.

Now this available ascending power has to support the weight of

1. The motor.
2. The necessary stores, such as fuel, water, &c.
3. The cargo.

The proportionate weight to be allotted to each of these respectively will depend on various considerations which it is impossible to reduce to any general rule. For the present purpose

attention may be confined to the first item, the motor; and there may be allotted to it a proportion of the whole available weight represented by r ; so that the weight of the engine, or whatever the motor may be, will be $= r (A d - B) dl$.

If then S represent the weight of the motor for each (useful) HP., then—

$$\text{Useful HP. of motor carried} = \frac{r}{S} (A d - B) dl \quad . \quad . \quad (I.)$$

The next question is how the power of the motor is to be expended.

The first element in the calculation is the resistance of the balloon to motion through the air. This is a point of great importance, and it will be necessary to treat it more at length hereafter. For the present, it may be safely assumed, in accordance with the analogy of bodies moving in fluids generally, to vary, for moderate speeds, as the square of the velocity, and it may be represented by $X v^2$, where X is a coefficient depending on the dimensions and form of the balloon.

The HP. necessary to propel the balloon at a given velocity v , will be equal to the resistance multiplied into the velocity, and divided by a certain constant number dependent on the units in which the quantities are taken. Call this H . (For resistance in lbs. and velocities in feet per minute, $H = 33,000$. For velocities in miles per hour, $H = 375$; in feet per second $H = 550$.)

Hence—

$$\text{HP.} = \frac{X v^3}{H},$$

which represents the power necessary to propel the balloon through the air.

The next question is as to the *efficiency of the propeller*. This has been often investigated for water navigation. Rankine, in his elaborate article on "Propellers,"¹ gives the efficiency of the screw of the "Warrior" $= 77\frac{1}{2}$ per cent. Mr. Isherwood² makes that of two small boats by Maudslay and Penn $= 65\frac{1}{2}$ and $71\frac{1}{2}$ respectively. Mr. Froude³ reduces it, for high speed working, to $57\frac{1}{2}$, but this great loss is attributed to causes which would hardly apply to air navigation. M. de Lôme estimated the efficiency at $72\frac{1}{2}$ per cent., taking a probable "slip ratio" of $21\frac{1}{2}$ per cent.

¹ Trans. Inst. Naval Architects, 1865.

² Article by Mr. Pendred. *Ibid.*, 1876.

³ *Ibid.*, 1876.

But, as will be hereafter shown, the actual slip in his trial was a little greater, and therefore the efficiency may be put down at 70 per cent., which is fairly borne out by nautical experience. According to this, for every 7 HP. directly expended in propelling the vessel, 10 HP. must be applied to the screw shaft, and the equation becomes—

$$\text{Useful HP. of motor carried} = \frac{10 X v^3}{7 H} \quad . \quad . \quad . \quad . \quad (II.)$$

Equating now (I.) and (II.) and reducing—

$$v^3 = \frac{7 r H}{10 S X} (A d - B) d l.$$

If all dimensions are expressed in feet, weights and pressures in lbs., and velocities in feet per second, then $H = 550$, and

$$v^3 = \frac{385 r}{S X} (A d - B) d l \quad . \quad . \quad . \quad . \quad . \quad . \quad (III.)$$

An equation which expresses, in a compact form, the relations between the chief elements that enter into the problem.

The next step is to obtain the values of the important coefficients A , B , and X .

Ascending power.—Supposing the balloon to be filled with pure hydrogen the levity of one cubic foot, at 32° Fahrenheit, and under one atmosphere, will be $= 0.0751$ lb. The volume of the balloon, according to M. de Lôme's proportions, was about $0.434 d^2 l$ cubic feet, so that on this supposition the floating power would be $= 0.0327 d^2 l$. In fact the floating power was $= 0.03 d^2 l$. The coefficient may therefore be taken at its lower value, *i.e.*

$$A = 0.03.$$

Weight of the structure.—There is no means of calculating this *à priori*, as it comprehends such a variety of items, dependent entirely on practical considerations. The coefficient must therefore be taken from examples on record. In M. de Lôme's balloon the weight was 3885 lbs. $= 0.673 d l$; in M. Giffard's it appears to have been less. The former is the more authoritative, therefore

$$B = 0.673.$$

Resistance of the balloon to motion through the air.—This is the most important element of the whole investigation, and is at the

same time the most difficult to determine, from the scarcity of experimental data on a large scale. It is, however, some palliation of the difficulty to know that the resistance of vessels propelled in water is also a quantity liable to much variation and uncertainty, notwithstanding the large amount of experience gained in water navigation. The proper course to adopt here is to apply mechanical analogies as carefully as possible.

The resistance of ships to motion through water may be estimated according to either of three elements of their dimensions:—(1) The area of immersed midship section; or (2) the skin friction; or (3) the cubic displacement. It will be advisable to apply each of these to the case of the balloon, and see how they correspond.

(1) *By the midship area.*—This plan was adopted by M. de Lôme, and the following is a *résumé* of the way he treated it. He proposed in the first instance to get a velocity of 8 kilometres (4·97 miles) per hour. He took the resistance to a plane surface passing perpendicularly through the air at this speed at 0·665 kilogramme per square metre. But, as is well known, this is reduced in a very large proportion by the pointed form. The elaborate modern investigations of Mr. Froude have shown that, theoretically, the head resistance may be almost annihilated if the most suitable form is adopted; and M. de Lôme gives, as a matter of practical experience, the fact of a reduction, in well-formed steamers, to an amount varying between $\frac{1}{40}$ and $\frac{1}{30}$ of the resistance due to the midship section. For his aerial structure, however, he was content to allow a double proportional resistance, taking the coefficient for the balloon at $\frac{1}{20}$. For the car, accessories, and suspending apparatus he took a coefficient of $\frac{1}{2}$. This brought out the resistance as follows:—

	Square metres.	Kil.
Balloon	$154 \times 0\cdot665 \times \frac{1}{20} = 5\cdot12$	
Car, &c.	$14 \times 0\cdot665 \times \frac{1}{2} = 4\cdot68$	
	Total resistance = 9·80	
	= 21·6 lbs.	

This would be the quantity $X v^2$ for a velocity of 7·3 feet per second, and a midship diameter of 48·67 feet. From which it follows that the resistance, estimated according to this method,

$$= 0\cdot000171 d^2 v^2.$$

The calculation may be checked in another way. According to the data of wind pressures usually adopted by English engineers,

namely, those given by Smeaton to the Royal Society, in his Paper on Windmills, the pressure on each square foot of flat surface = $\frac{1}{437} v^2$, where v is in feet per second.

The area of the midship section will be = $\frac{\pi}{4} d^2$; and that of the car, &c., may be taken at $\frac{1}{11}$ of this. Hence, allowing the same reductions for the form as M. de Lôme did, the total resistance—

$$= \left(\frac{\pi}{80} d^2 + \frac{\pi}{88} d^2 \right) \times \frac{v^2}{437} \\ = 0.000172 d^2 v^2,$$

agreeing almost identically with M. de Lôme's estimation.

(2) *By the skin friction.*—This is a mode which has been sanctioned by recent scientific investigations. Professor Rankine has stated¹ that if W = wetted surface of a ship in square feet, the resistance in lbs. may be taken as = $\frac{C W (\text{speed in knots})^2}{100}$

where C is a constant something greater than unity, whose exact value depends on the lines of the vessel.* For the "Warrior," 9000 tons, he found it = 1.275; for the "Fairy," 168 tons = 1.124. Taking the higher value and putting v = the speed in feet per second, the resistance will be

$$= \frac{W v^2}{224}.$$

Now if air be substituted for sea water the resistance will be diminished in the ratio of the densities, *i.e.* 793 to 1; and further, the surface of the balloon exposed to the friction of the surrounding fluid may be taken as proportionate to dl : in M. de Lôme's structure it was about = $2.3 dl$. Hence on this mode of estimation, the resistance for the balloon, taken on the same coefficient as the "Warrior," will be

$$= \frac{2.3 dl v^2}{224 \times 793} \\ = 0.00001295 dl v^2.$$

Adopting then Mr. de Lôme's allowance, for the balloon, of double the proportional resistance for a good ship, and adding, as he also does, 88 per cent. for the car, &c., the resistance comes out according to this mode of estimation

$$= 0.0000477 dl v^2.$$

(3) *By the displacement.*—This mode combines both the former

¹ Trans. Inst. Naval Architects, 1864 and 1865.

elements of midship section and skin surface. If D = displacement of a vessel in tons, and v her speed in knots per hour, then the rule given is ¹—

$$\text{Resistance in lbs.} = C \times v^2 D^{\frac{2}{3}},$$

where C is a coefficient varying from 0.8 to 1.5, according to the form and condition of the ship. Taking $C = 1$ for a moderately good example, and changing D to cubic feet, and v to feet per second, the resistance is

$$= \frac{v^2 D^{\frac{2}{3}}}{30 \cdot 5}.$$

The displacement of the balloon has been given already as $= 0.434 d^2 l$, and proportioning for the densities of air and sea water, the resistance becomes

$$= 0.0000238 d^{\frac{4}{3}} l^{\frac{2}{3}}.$$

Increasing as before, and adding for the car, &c., it is

$$= 0.0000886 (d^2 l)^{\frac{2}{3}} v^2.$$

These three values of the resistance may be compared in the case of any balloon where the proportion of length to diameter is given. In M. de Lôme's balloon, for example, $l = 2.43 d$. Substituting this and reducing, the resistance becomes, when estimated

$$\begin{aligned} \text{By midship section} &= 0.000172 d^2 v^2; \\ \text{,, skin friction} &= 0.000116 d^2 v^2; \\ \text{,, cubic displacement} &= 0.000160 d^2 v^2. \end{aligned}$$

The estimation by skin friction is the smallest, for the obvious reason that in this structure the proportion of length to transverse dimensions is so much less than is usual in ships. The general comparison, however, shows that the estimate by midship area adopted by M. de Lôme, is fairly corroborated by other methods quite independent, and it may therefore be safely taken as representing the resistance.

It is now possible to apply the formulæ to M. de Lôme's case, and see how the results correspond with those of experiment. The values of S and r must, however, be first obtained from his data.

¹ Rankine, "Rules and Tables," p. 274.

The motive power he used was eight men, and he states that, when they were all working together, they produced $\frac{8}{10}$ of a horse power. The men weighed 1325 lbs., which gives—

$$S = 1656.$$

And as his total available ascending power was 2,046 kilograms = 4515 lbs., the proportion r allotted to his motor was $\frac{1325}{4515} = 0.3$ nearly.

Returning now to equation III., and making $l = 2.43 d$, and $X = 0.000172 d^2$, it becomes—

$$v^3 = 440,000 \frac{r}{S} (A d - B).$$

Wherefore, inserting the values of A , B , r , and S , previously given, the velocity comes out = 9.2 feet per second, or

$$= 6.25 \text{ miles an hour,}$$

which is almost identical with the speed actually obtained on the trial.

This agreement of the calculated and the observed velocities shows, in the first place, that the result obtained by M. de Lôme is in perfect accordance with what might be expected according to ordinary mechanical laws; and secondly, it gives a practical warrant for the more extended application of the reasoning. It is clear that since the power exerted is known, the estimate made of the resistance must hold good, at any rate for moderate velocities; and although there are no experimental data for higher speeds and greater power, yet the analogy of experience in marine engineering will justify the wider application of the rules, if the principles on which they are constructed are sound.

It is therefore proposed to examine what might be expected to be the performances of dirigible balloons, if, in the provision of their power, due advantage were taken of the most recent improvements in mechanical engineering.

It will be evident that the kind of power used by M. de Lôme was exceedingly disadvantageous, by reason of its great weight. He fully admitted this, but his object was a limited one, and, under the circumstances, he took, no doubt, the wisest mode of attaining it; for an independent velocity of a few miles an hour would, by taking proper advantage of the wind, certainly have sufficed to enable balloons to enter the city. For more extended applications,

however, human power is out of the question, and it is necessary to go back to M. Giffard's plan of using steam, with which, for this purpose, no other kind of motor at present in use could compete.

But although steam power is lighter than that of men, still down to a late period it has been too heavy to be of any real utility in a case of this kind, where the carrying capability is so limited. According to the usual practice with engines used for steam navigation, it may be reckoned that the motor employed has weighed 4 to 5 cwt. per HP., which is also about the weight of small fixed engines in the ordinary market at the present day. At this rate the amount of power which could be carried in a balloon would be so small as not to do much towards the successful solution of the problem of aerial navigation.

But recent improvements have much changed matters in this respect; for in cases where economy of weight has been desirable, the skill of engineers has succeeded in effecting it to a very remarkable extent. In the modern locomotive, for example, much has been done to increase the power that can be developed by an engine of a given weight, and if those parts are excluded which properly belong to the vehicle, and not to the engine, the weight would probably come out not more than about 1 cwt. per HP.

But even this has been much improved upon within the last few years, as will be seen by the Paper by Mr. Thornycroft, already referred to. It shows that in the arrangements of power for the light boats there described, the Author has succeeded in bringing the weight of the whole propelling machinery down to 43·5 lbs. per indicated HP.; which, omitting the screw and its long shafting and bearings, would probably give not much more than 40 lbs. for the motor alone. In the discussion which followed the reading of the Paper, opinions of high authority were expressed that further reductions were possible, particularly in regard to the boiler; but the figure already obtained will suffice for the present object.

It is, however, necessary, in order to make this correspond with the terms of the foregoing formulæ, to transform it into the weight per *useful* HP. The loss between the power indicated in the cylinders and that available at the end of the crank-shaft varies of course in different engines, but it is usually reckoned from 15 to 25 per cent. Professor Rankine estimated the loss on the engines of the "Warrior" at 22½ per cent.; Mr. Isherwood made that of Maudslay's and Penn's engines 13 and 14½ per cent. respectively. Mr. Froude estimated it higher, namely 33·3 per cent.; of which

7.1 per cent. was due to the several pumps. In engines of the light and simple character of those here contemplated, without any air, bilge, or condensation pumps, probably 20 per cent. allowance would be ample; *i.e.* for every 4 HP. applied to the screw shaft, 5 HP. must be indicated in the cylinders. This brings the weight to something over 50 lbs. per useful HP.

But there is another point to consider. If steam power is used, the weight of a store of fuel and water must be also taken into account in the burden to be carried. The consumption of fuel for the lightest engines is given by Mr. Thornycroft at a little under 4 lbs. per indicated HP. per hour; probably some kind of liquid hydro-carbon might be most advantageous for this purpose, and might also lead to a reduction in the weight to be carried.

The water, however, is at first sight a more formidable consideration, the quantity necessary being from 25 to 28 lbs. per HP. per hour. Such a large addition would, a few years ago, have rendered steam-ballooning almost impracticable; but fortunately here again recent improvements have come in aid. The water used in steam engines is not, like the fuel, decomposed and dissipated; it is only changed in form, and can be reproduced by cooling. M. Giffard saw this, and with the skill of an accomplished practical engineer he proposed to introduce a system of air condensation. The Abbé Moigno gave, in the "*Mondes*" of 15 Oct., 1863, an account of various improvements which M. Giffard had then on hand, and the following passage refers to this point:—

"The provision of water which it is possible to carry in the air being necessarily very limited, it is desirable to use the same water, by condensing the steam after it has produced its mechanical effect. This new improvement has been carried out as rapidly as the former ones; any of our readers may, whenever they please, see, in the Avenue de Suffren, No. 40, suspended to the ceiling of the workshop, a series of flat tubes offering a large surface, which condense the steam of a 10-horse engine."

The air-condenser has been used in this country by Mr. Perkins and Mr. Cradock, and it has within the last year or two been successfully applied by Messrs. Kitson and Co. to tram-cars running in the streets of Leeds. It is therefore no longer a mere theoretical possibility, but an accomplished fact in steam-engineering. From data the Author has obtained it appears that with a moderate surface about three-fourths of the water may be recovered, and that a condenser adapted to this purpose may be estimated to weigh about 20 lbs. for each useful HP. of the engine.

From these data the weight may now be made up more accu-

rately. The weight of the engine, with the condenser, may be taken at 75 lbs. per useful HP., *i.e.*

$$S = 75,$$

instead of 1656, as in M. de Lôme's balloon.

The store of fuel and water necessary to be carried may be estimated, according to present data, at from 10 to 12 lbs. per HP. per hour; but there is little doubt that this quantity, as well as the weight of the engine, could be reduced if the necessity for doing so should arise.

In proceeding now to apply the formulæ to new cases, it is necessary to determine a proportion of length to diameter. This in M. de Lôme's case was made 2.43; in M. Giffard's balloon, it was 3.66. There can be no doubt of the advantage of length in diminishing the proportion of resistance to capacity, and in giving better steering properties; and even M. Giffard's proportion (which he found answer perfectly well), is very small when compared with those common in water navigation. In the following calculations, therefore, the proportion $\frac{l}{d} = 3\frac{2}{3}$ will be adopted.

This will lead to a new comparison of the estimated resistance, as determined by different methods. By substituting the value of l in terms of d in the various resistance equations, it will be found that the following values appear—

$$\begin{aligned} \text{By midship section} &= 0.000172 d^2 v^2; \\ \text{,, skin friction} &= 0.000175 d^2 v^2; \\ \text{,, cubic displacement} &= 0.000211 d^2 v^2. \end{aligned}$$

Here, it will be observed, the effect of the increased length is to bring out higher values of the resistance according to the two latter modes of estimation. On this ground it will be safer to adopt them in preference to the former; and in the absence of any special experience as to which of the two is the more applicable, the mean may be taken, *i.e.*

$$X = 0.000193 d^2.$$

It is further necessary to determine r , the proportion of ascending power to be devoted to the motor, and this may be conveniently made one-third. A sixth may then be added for a store of fuel and water, which would suffice to keep up the maximum power for three or four hours, but would last much longer under ordinary working, when advantage would be taken, to the

utmost extent possible, of the direction of the wind. (This store of consumable material might take the place of the ballast used in ordinary aerostation.) The remainder of the net ascending power, one-half, would be available for cargo.

It may be advisable to add to the constant B , to allow for some increased weight that may probably be necessary to meet an increase of power and speed. Instead of 0.673 , let

$$B = 0.72,$$

an increase of 7 per cent. on the whole weight of the structure.

Substituting the above values in equation III., it becomes, in round numbers, for the maximum possible speed through the air—

$$\begin{aligned} v^3 \text{ in feet per second} &= 975 (d - 24) \quad . \quad . \quad . \\ v^3 \text{ in miles per hour} &= 313 (d - 24) \quad . \quad . \quad . \end{aligned} \quad \text{(IV.)}$$

It remains to say something of the necessary size and velocity of the screw-propeller. This instrument must, no doubt, be large, owing to the comparative rarity of the medium against which it is to act; but an idea may be formed of its proportions according to the analogy of water navigation.

In regard to the diameter, the usual rule is to make the area of the screw circle proportional to that of the immersed midship section. M. de Lôme states that the most favourable proportion, for good ships, is $\frac{1}{4}$; but considering the increased coefficient of resistance which he had allowed for his vessel, he fixed the diameter of his screw at 9 metres, which gave a proportion to the area of $\frac{63\frac{1}{2}}{168}$ or $\frac{1}{2.65}$. In English steamers,¹ the proportion varies

a great deal, but it may generally be taken as from $\frac{1}{2.5}$ to $\frac{1}{3.5}$.

M. de Lôme's screw was very nearly $\frac{3}{8}$ the maximum diameter of the balloon, and, in default of any experience to the contrary, this proportion may be retained.

In order to calculate the velocity of rotation, it is necessary to estimate the amount of slip. In M. de Lôme's trial, the pitch of the screw was 8 metres, the number of revolutions $27\frac{1}{2}$ per minute, and the speed of the balloon 169.2 metres per minute. Hence the advance of the vessel for each revolution was 6.15 metres, giving a "slip ratio" of $\frac{1.85}{8}$, or about 23 per cent.

¹ See data for a very large number of screw ships in "Bourne on the Screw Propeller." 4to. London, 1867.

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M. de Lôme's pitch was $\frac{8}{9}$ the diameter, but this is unusually fine, the general ratio varying from 1 to 1.5. With steam power, no doubt the pitch might be advantageously increased, but in the absence of experience it may not be advisable to depart too widely from what has been done, and the ratio may be put = 1. M. de Lôme originally proposed this pitch, and why it was reduced he does not explain.

Calculating on the above slip and pitch, if n = revolutions per minute—

$$n = \frac{78 v}{\text{diameter of screw}},$$

or, reverting to equation IV.—

$$n = 1,160 \frac{(d - 24)^{\frac{1}{3}}}{d},$$

which will give the number of revolutions for the maximum speed of any diameter of balloon on the data before named.

Returning to equation IV., the expression shows that a certain magnitude of balloon is necessary to obtain any power of navigation, and that the capability will increase with the diameter. Some different sizes may be calculated in order to illustrate the application of the formulæ, and the results are shown in the following Table.

DIRIGIBLE BALLOONS.

As calculated from data in accordance with the actual trials of Messrs. Giffard and Dupuy de Lôme, combined with the results of the most recent improvements in steam motors.

	Feet. 30	Feet. 40	Feet. 50	Feet. 75	Feet. 100
Maximum diameter	110	147	183	275	367
Length					
	lbs. 2,970	lbs. 7,040	lbs. 13,750	lbs. 46,400	lbs. 110,000
Total ascending force . . .	2,370	4,220	6,600	14,850	26,400
Weight of structure	600	2,820	7,150	31,550	83,600
Available ascending force . .					
HP. of motor	3	12	32	140	370
	Cwt. 2½	Cwt. 12½	Cwt. 32	Tons. 7	Tons. 18½
Weight disposable for cargo, after allowing for fuel and water					
Maximum speed through the air miles per hour	12	17	20	25	29
Diameter of screw . . . in feet	18	24	30	45	60
Revolutions per minute for maximum speed	76	81	77	64	55

The smallest size of balloon that would be of any use would be about 30 feet diameter. This would carry an engine of about 3 HP., giving a maximum speed of 12 miles an hour. The weight available for cargo would be, however, only about sufficient for one person.

Next take 40 feet diameter, the size of M. Giffard's balloon. This would carry 12 HP., would attain 17 miles an hour, and would carry $12\frac{1}{2}$ cwt. of cargo. M. Giffard's engine was only 3 HP., but his balloon was inflated with common coal-gas instead of hydrogen, and was therefore deficient in ascending force. The power he had ought to have produced a speed of 10 miles an hour; the reason his result fell so much short of this was the small size of the screw, which was only about one-fifth the proper area, and was therefore quite unable to utilise beneficially the power employed. It is well known, in water navigation, that the loss by slip increases largely when the screw is unduly reduced in size.

The next example is about the size of M. de Lôme's balloon, 50 feet diameter, and the calculation shows what it would have done had he used more favourable proportions, and availed himself of the modern steam power. He could, at this rate, have carried an engine of 32 HP., which would have turned his screw three times as fast, and would have given him, with the higher pitch, a speed of 20 miles an hour.

By increasing the diameter to 75 feet, the balloon would have a velocity of 25 miles per hour. Even 100 feet diameter would not be an unreasonable magnitude, and this, keeping the same proportion of power to weight, would give a speed through the air approaching 30 miles an hour, and would have $18\frac{1}{2}$ tons disposable for cargo.

These are no doubt startling results, but they arise legitimately from the data now in existence, and it will be seen that their significance, in giving a new aspect to the problem of aerial navigation, is largely due to the mechanical improvements effected in quite recent times. Before the invention of the screw propeller, there were no feasible means whatever of attacking the problem; and even after Giffard and Dupuy de Lôme had shown how the screw might be applied, it was not till within the last year or two that the weight of the motor and its stores had been so reduced as to give any hopeful prospect of useful results. That there is now such a prospect, so far as mechanical reasoning can justify it, hardly admits of a doubt.

PRACTICAL CONSIDERATIONS.

It only now remains to inquire into some of the more important considerations bearing on the question in a practical point of view.¹ And these divide themselves into two classes:—first, as to the construction of the balloon, and secondly, as to its use.

In regard to the first head, the provision of the gas, and its preservation in an envelope that shall be at once light, impervious, and strong, are conditions of ordinary study for balloons generally. M. Giffard devoted much attention to them, and the large captive balloons he constructed were filled with hydrogen at a very moderate cost, which was retained for a long period with scarcely any loss. M. de Lôme also considered his arrangements in this respect satisfactory. All other matters of a strictly aeronautical character, may safely be left to the many eminent experts in the art.

But for this purpose an unusual form of balloon is necessary, and important questions arise as to its stability. M. de Lôme, with his great experience in analogous questions in naval architecture, saw the importance of this point, and took great pains to investigate the problem. His reasonings may be found fully detailed in the “*Comptes Rendus*,” and it will suffice here to say that he not only determined the stability theoretically, but found his expectations fully borne out by the result of his trial. M. Giffard before him had had doubts on the subject, but adds that his experiment had fully reassured him, and had shown that the use of an elongated balloon was in all respects the most advantageous possible.

As an instance of the care bestowed by M. de Lôme on the mechanical design, one contrivance is worth mention. As a balloon rises or falls, the contained gas expands or contracts in bulk, by reason of the variation in the atmospheric pressure. With the ordinary globular balloon the envelope is only partially filled at starting, and room is left in the lower part for the expansion. But with a navigable balloon it is desirable that the external shape should be maintained smooth and unaltered at all elevations. This M. de Lôme accomplished by taking advantage of a suggestion made by General Meusnier at the end of the last century, namely, by putting inside the balloon an air-pocket, or reservoir, the expansion or contraction of which would compensate for any

¹ The Author has found it necessary, for the sake of completeness, to incorporate in this Paper some passages previously published elsewhere.

difference in the bulk of the gas caused either by variation in height or by loss in escape or leakage. This internal vessel was controllable from the car, and it might be given a more extended application in regulating the vertical movements of the balloon generally. M. de Lôme states that the behaviour of his balloon, not only as to stability, but as to ease of management, was all that could be desired.

In regard to the propelling apparatus, the design of a suitable steam motor would be only a simple task to mechanical engineers accustomed to work of the kind. The construction of the propeller itself would involve more difficulty, owing to the absence of experience on any large scale of power and speed; for in large balloons it must be of considerable size. M. de Lôme made one of 30 feet, which appears to have answered very well for his small speeds; but with the higher velocities the thrust would be of course increased. The 30-foot screw, when propelling at 20 miles an hour, would have to convey a thrust of about 360 lbs., and this would require a corresponding increase of strength. For the largest balloon in the Table the screw must be 60 feet diameter (about the usual size of a windmill), and it would convey a thrust of about 3,000 lbs. The design and construction of such screws, so as to make them combine the necessary strength with the necessary lightness, would no doubt call for considerable mechanical skill.

There is also another point requiring attention, in regard to the position of the screw. To maintain perfect stability during the propulsion through the air, the propelling force ought to act in a horizontal line with the centre of all the resistances, which would be a little below the line of the axis. When it is placed lower, there results a tendency to throw the balloon a little out of level. M. de Lôme calculated this, and found the deflection was, in his case, less than a degree, which was inappreciable. At higher speeds it would be increased, and probably, with a 100-foot balloon, propelled at 30 miles an hour, it might amount to several degrees, and its effect would require correction in some way.

An arrangement must also be made to meet the disturbing effect of the loss of weight by the consumption of fuel and water, without wasting the gas; probably M. de Lôme's internal pocket might be made useful for this purpose also.

These are, however, after all, only matters of practical mechanics, and one cannot doubt the ability of engineers of the present age to deal with them satisfactorily if the requirement should arise. On the ground, therefore, of practical construction, there appears no reason to doubt the feasibility of carrying out the

principles arrived at by theoretical considerations. It is possible that by practical necessities the estimated weights or resistances might be somewhat increased; but there is considerable margin for this, and it must be borne in mind that all the data have been taken on things as they are. When the whole arrangement came to be carefully studied and tried, it is certain that improvements would take place, and what might be lost in some particulars would probably be recouped in others.

But, assuming that dirigible balloons can be constructed, it is desirable further to inquire what practical considerations might affect their use.

It is hardly necessary to say that the introduction of a locomotive machine which would transport a large number of people through the air, in any direction required, at the rate of 20 or 30 miles an hour, would be a remarkable novelty, and would offer many advantages. Comparing it with ships and boats, it would be far swifter, much less expensive in first outlay and cost of working, would require no harbours, would produce no sea-sickness, and would escape the greatest dangers inherent in water navigation. As a means of land transport, it would be quicker than common road travelling, and would compare fairly with the ordinary speed on railways, while it would dispense with the costly provisions requisite for both these modes of getting over the ground, and would be free from the multitude of liabilities to accident attending them.

But it may naturally be objected that such a mode of locomotion would have peculiar dangers of its own. No doubt balloons have hitherto been very subject to accidents, and the bare idea of anything going wrong at a height of thousands of feet above the earth is very appalling. But much of this impression will vanish before common-sense reasoning. It must always be borne in mind that for the purpose of locomotion there would be no reason for ascending high into the air; it would only be necessary to keep at a sufficient altitude to clear terrestrial impediments, and this would not only do away with much of the terror of the idea, but would greatly increase the probability of a safe escape from accidents of whatever kind.

It is worth while to consider in what direction danger might, in extreme cases, lie. The loss of gas, by rupture of the envelope or otherwise, is a remote possibility; but the experience of many actual cases has proved that the resistance of the air to the large surface exposed has sufficed to prevent any rapid fall. Special

measures might be easily provided, and at low elevations over land no serious catastrophe need be feared on this ground. In crossing over water precautions would still be possible, and the case would not be so hopeless as in many marine casualties. The danger of fire, if properly guarded against, need not be greater than in a ship at sea. Indeed, M. Giffard, who has tried the experiment, expressly states that the idea of such danger is quite an illusion.

The accidents that arise to ordinary balloons almost always occur in the descent, which, if the wind is high, requires great care and skilful management. In this case the propelling power would be most especially useful; the aeronaut could choose his place of landing with precision, and by turning his head to the wind he could avoid the dragging which is so dangerous, and which has so often brought a fatal termination to balloon voyages.

On the whole there can be no good reason to believe that the danger would be more formidable with this than with other kinds of locomotion. One cannot ignore the frightful casualties that so frequently now occur in land, river, and sea traffic; and when it is considered how many of their causes would be absent in the free paths of the air, one may even venture to assert that balloons would be the safest, as well as the pleasantest, mode of travelling.

As a set-off against this, however, there is one great disadvantage attending aerial locomotion, namely the *uncertainty* it must always be liable to, in consequence of the effect of the wind. The course of any floating vessel is naturally affected by the general motion of the medium in which she floats. With water the currents may amount to a few miles an hour; with air they will be much more, so much as seriously to interfere with the locomotive capabilities of the balloon.

According to data gathered from the meteorological reports of Greenwich Observatory for the year 1877, it appears that—

Miles per Hour.					
During 17 days in the year the mean velocity of the wind was between 0 and 5					
" 103	"	"	"	"	5 " 10
" 127	"	"	"	"	10 " 15
" 75	"	"	"	"	15 " 20
" 29	"	"	"	"	20 " 25
" 10	"	"	"	"	25 " 30
<hr/>					
361					
" 3	"	"	"	"	30 " 35
" 1	"	"	"	"	35 " 40
<hr/>					
365					
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The mean over the whole year was 13 miles an hour. At higher levels these velocities are exceeded; but, as has been before stated, if balloons were used for the purposes of locomotion, there would be no necessity for them to travel at any great altitude.

Now the course of a navigable balloon will be, like that of a steamer in a tideway, a compound of its own independent velocity with that of the general motion of the surrounding medium. This can easily be calculated by the ordinary rules of navigation, and the following Table shows the manner in which the composition of the two motions will influence the locomotive capability of the moving body. It is formed on the assumption that an independent speed of 30 miles an hour might be given to the balloon, and that the wind blows with velocities varying from 0 to 50 miles an hour. The wind is assumed due north, but the relations will be the same for any other direction.

AERIAL NAVIGATION.

TABLE showing the speed, in miles per hour, that could be commanded on any proposed course, by a dirigible balloon having an independent motion through the air of 30 miles per hour. Wind supposed due north, blowing with velocities varying from 0 to 50 miles per hour.

PROPOSED COURSE.

Velocity of Wind.	N.	N.N.E. or N.N.W.	N.E. or N.W.	E.N.E. or W.N.W.	E. or W.	E.S.E. or W.S.W.	S.E. or S.W.	S.S.E. or S.S.W.	S.
Calm	30	30	30	30	30	30	30	30	30
5	25	25	26	27	29	31	34	35	35
10	20	20	22	25	28	33	37	39	40
15	15	15	17	20	25	32	39	44	45
20	10	10	13	16	22	31	41	48	50
25	5	5	7	9	17	29	43	51	55
30	..	..	..	..	..	22	43	56	60
35	..	..	..	..	..	..	42	59	65
40	..	..	..	..	..	..	38	63	70
45	..	..	..	..	..	..	..	67	75
50	..	..	..	..	..	..	..	70	80

The practical result of this would be as follows:—

(1.) In storms and gales, say exceeding 40 miles an hour, it would not be prudent for the balloon to travel at all. Ships only sail "wind and weather permitting," and balloons must submit to the same restriction.

(2.) In high winds, say from 30 to 40 miles an hour, it could only go in a course generally corresponding with that of the wind; but it would still have a considerable range of direction and a high velocity, and, what is of the greatest importance, it would have the power of steering, and would be able to command its descent at any time, and in any place, without danger.

(3.) In light and moderate winds, under 30 miles an hour, which the Greenwich observations record to prevail all the year with the exception of a few days, it could travel in any direction, the speed varying from 5 to nearly 60 miles an hour.

It must also be added that with contrary winds the voyages must be necessarily short distances at a time, from the impossibility of carrying large stores of fuel and water to keep up the full power for any long period. But with favourable winds, such as the trades, almost any distance might be run, as the use of the engine would be limited to what was necessary for steering purposes.

These conditions would no doubt render aerial navigation unsuitable for traffic that requires regular and punctual transit, and would therefore much limit its commercial value. It could never, for such purposes, compete with railways, or lines of river or sea navigation. But still a great variety of cases exist where its peculiar advantages would tell in practical use; and probably, if such a means of locomotion were once introduced, increased employment for it would soon arise.

SUMMARY.

The foregoing investigation appears to warrant the following conclusions.

1. The problem of aerial navigation by balloons is one as perfectly amenable to mechanical investigation as that of aquatic navigation by floating vessels; and its successful solution involves nothing unreasonable, or inconsistent with the teachings of mechanical science.

2. It has been fully established by experiment that it is possible to design and construct a balloon which shall possess the conditions necessary for aerial navigation, *i.e.* which shall have a form of small resistance, shall be stable and easy to manage, and, if driven through the air, shall be capable of steering by a proper obedience to the rudder.

3. If, by a power carried with the balloon, surfaces of sufficient area can be made to act against the surrounding air, the reaction will propel the balloon through the air in an opposite direction.

4. The modern invention of the screw-propeller furnishes a

means of applying power, in this way, to effect the propulsion; and the suitability and efficacy of such means have been shown by actual trial.

5. Sufficient data exist to enable an approximate estimate to be made of the power necessary to propel such a balloon with any given velocity through the air.

6. The recent great reduction in the weight of steam motors has rendered it possible to carry with the balloon an amount of power sufficient to produce moderately high speeds, say 20 or 30 miles an hour through the air; and by taking advantage of other recent improvements it would also be possible to carry a moderate supply of fuel and water for the working.

7. The practical difficulties in the way are only such as naturally arise in the extension of former successful trials; and such as may reasonably be expected to give way before skill and experience.

8. The practical utility of aerial locomotion must always be considerably restricted by the effect of the wind, which it is impossible for any flying body to evade. But still, such a system would have peculiar advantages of its own; and on the whole, dirigible balloons may form a feasible and useful addition to the present means of transport, and are therefore worthy the attention of the engineer.

Dec. 1881.