Peripheral Fans for GEM

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Existing GEM's are rather unsatisfactory, two major problem areas being performance and stability. It is shown that an important factor is the pressure loss that occurs in the ducting between the fans and the peripheral jet nozzles. As a result, the best system efficiency so far achieved is about 40%. This can be increased to perhaps as much as 80% by using peripheral fan installations because they eliminate the need for ducts. As additional bonuses, peripheral fans could result in substantially better stability, trim and control characteristics, and lower total lifting system weights. The peripheral eductor is mentioned as a special case of the peripheral fan. It is shown that, properly employed, the peripheral eductor matches well with a gas turbine air-supply and avoids the need for any mechanical components in the lift system. This elimination of fans, shafts, and gearboxes, with their attendant problems of weight, reliability, and vulnerability, might do much to counterbalance the increasing complexity of large GEM's.

Introduction

THE GEM portrayed in Fig. 1 was designed when the author was employed by Frost Engineering. At sea level it will hover at a height equal to 16% of its diameter, with a payload equal to 45% of its empty weight. It also has a higher power/weight ratio than some helicopters!

Designed as a feasibility model against an Army requirement to investigate a Mine Search Head Carrier (MSHC) that has no ground contact, it is a member of, or at least a second cousin to, the unfashionable "plenum chamber" breed. Rather surprisingly (and excluding some current troubles due to a replacement fan) it appears to be the most aerodynamically efficient GEM built so far. This was not anticipated by the author when he designed it [the specified government-furnished equipment (GFE) engine and vehicle size gave plenty of reserve], and we were slow to realize that this was so. It now appears that, although the MSHC GEM is not particularly efficient, other GEM's are even less efficient! In the context of mine detection without ground contact, there appears to be no effective alternative to the GEM, however, so that low system efficiency will not necessarily prevent its use.

Most GEM missions can be performed by other vehicles, however, so that efficiency becomes much more important. Efficiency in this connection has two meanings, the first relating to the "fundamental efficiency" of the concept which is the efficiency obtained when there are no system losses. For a hovering GEM, this is given by the (η = 100%) curve in Fig. 2, based on the theory of Refs. 1 and 2. Obviously, ships and wheeled vehicles are both more efficient in "hover," since neither requires the expenditure of any power.

Secondly, we have to be concerned with "system efficiency," which is the product of all the efficiencies in a given system. As shown in Fig. 2, a system efficiency of 40% is currently about the best achieved with existing vehicles. This is not at all good when compared with other vehicles, such as helicopters and fixed-wing aircraft.

The Aerodynamic Efficiency of Existing GEM's

Figure 2, which is based on Tables 1 and 2, shows that the best system efficiency for present day GEM's is only about 40%, the majority being grouped around 25%, with a few isolated cases, which are less than 10% efficient. When we compare this with the typical helicopter figure of 70%, we can see plenty of room for improvement. The three chief reasons for these low efficiencies are thought to be as described in the following three subsections.

Fan Design Problems

The fan characteristics are intimately connected with the aerodynamics of the vehicle, and a basically "good" fan may perform poorly when installed in a particular vehicle.

To take the simplest possible example, the blade elements of an axial fan should be operating at their maximum L/D ratio angle of attack at the design point operating height, but should not be stalled when the GEM is at lower heights. Also, the fan characteristics should be such that its flow

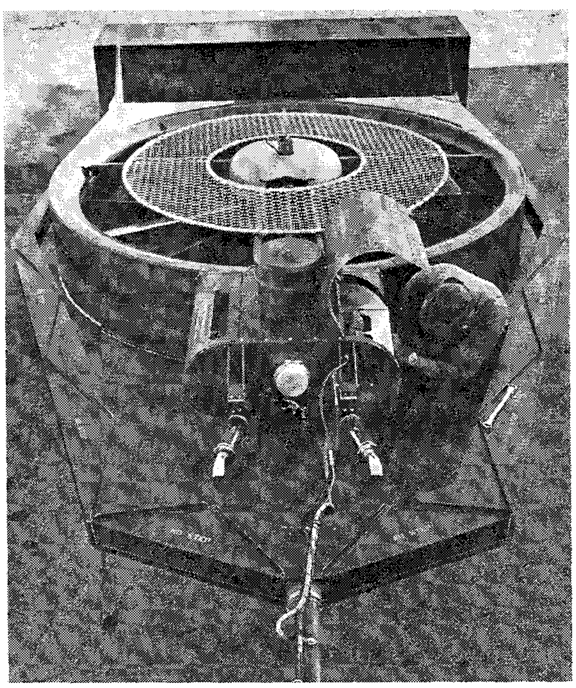

Fig. 1 The Frost MSHC GEM developed for ERDL, Fort Belvoir. The original conception was due to Joseph Boneta, Chief, Equipment Development Section, ERDL, who also developed a small scale model to prove system feasibility. The simulated search head shown here has now been replaced by a smaller ERDL design.

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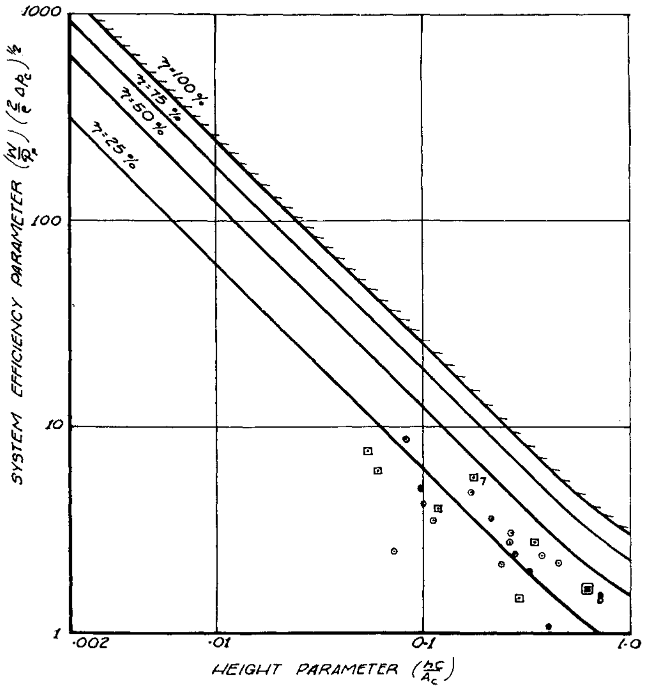


Fig. 2 Contours of "system efficiency" for annular jet GEM's. The vehicle data points are obtained from Tables 1 and 2.

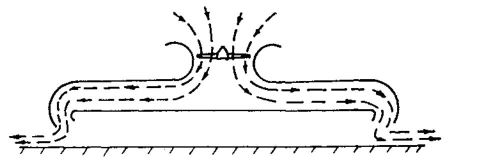


Fig. 3 Idealized GEM with a centrally located fan.

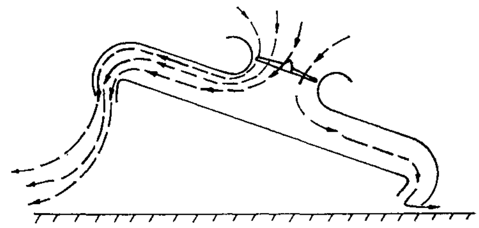


Fig. 4. Effect of perturbation in pitch or roll on an idealized annular jet GEM.

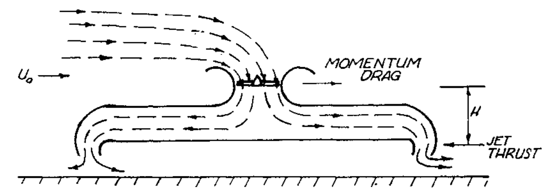


Fig. 5 Mechanism of nose-up pitch.

derivative $\partial\psi/\partial\phi$ should be large in a negative sense for good stability characteristics; that is, the pressure rise generated by the fan should decrease as the air mass flow through it increases. (If $\partial\psi/\partial\phi > 0$, self-excited instability can occur, as shown in Ref. 4.) Taken together, these requirements call for careful optimization of the fan geometry in conjunction with its associated ducting and in-ground proximity. Particularly when the fan has a large inflow ratio, it is found that the various conflicting requirements are mutually exclusive.

Extensive Ducting

The passage of air along a duct always involves losses, because of skin friction and diffusion losses. Considering the idealization in Fig. 3, for example, the duct skin area of an annular jet must be at least twice the planform area (A_T). When we allow for the necessary structural frames, this figure is more nearly $4A_T$. Thus the skin-friction loss is roughly

$$\Delta P_{SF} = C_f \tfrac{1}{2}\rho v^2 4(A_T/A_F) \quad (1)$$

where

ΔP_{SF} = loss of total head due to skin friction
v = mean velocity in the duct
C_f = skin-friction coefficient
A_F = fan area

We can expect a pressure loss of about 0.2 ($\frac{1}{2}\rho v^2$) around a well-designed right-angled bend, so that the total pressure losses up to the nozzle for the configuration of Fig. 3 will be

$$\Delta P_{SF+b} = \tfrac{1}{2}\rho v^2[0.4 + 4C_f(A_T/A_F)] \quad (2)$$

Thus about half the energy put into the air by the fan is likely to be lost again by the time the air reaches the nozzles. A diffuser behind the fan, to convert kinetic energy to pressure energy and hence reduce the velocity (v), is an obvious way of reducing this loss. However, because of space limitations, it is usually found that the diffuser loss just about balances the savings introduced in this way.

Compromises to Achieve Stability

When the configuration of Fig. 3 is tilted with respect to the ground plane, the back pressure at the low nozzle is increased, and less air emerges. Thus the momentum flux from the high nozzle is increased as indicated in Fig. 4. This means that pitch stiffness is very low, if not actually negative, and also gives rise to a horizontal force, which couples pitch to the translation degree of freedom, a classic method of introducing dynamic instability (e.g., the hovering helicopter).

When the fan is large enough to generate useful corrective moments, an obvious solution is compartmentalization that extends right up to the fan. This is done with the MSHC GEM illustrated in Fig. 1, and the result is (we are told by qualified observers) the most stable GEM yet flown. The losses involved in compartmentalization are fairly small (about 10% pressure loss) and the structural weight negligible in this example.

Table 1 Efficiency of some existing GEMS: plenum chamber vehicles, mainly from Ref. 3

Company	Model	Planform, ft	h	bhp/W	Δp_c	hC/A_c	$(2\Delta p_c/\rho)^{1/2}$	$\frac{P_F/W}{(2\Delta p_c/\rho)^{1/2}}$
Bell Aero	2015	18.0 × 8.0	2.0	0.03245	13.88	0.0601	108.0	0.1652
Bell Helicopter	Scooter	7.1 × 4.6	2.0	0.0444	11.02	0.1193	96.3	0.2535
Bertelson	Aeromobile	8.4 × 5.9	6.0	0.1235	11.73	0.288	99.3	0.684
Curtis	ACM-1-1	16.0 × 11.0	1.0	0.0567	8.53	0.0255	84.7	0.3685
Curtis	ACM-2-1	21.0 × 8.0	12.0	0.0867	20.6	0.345	131.7	0.362
Goodyear	...	8.0 × 5.0	1.0	0.035	25.0	0.054	145.0	0.1327
Spacetronics	HydroAire	30.0 × 24.0	14.0	0.0317	11.8	0.175	99.6	0.175
Frost	MSHC GEM	8.0 × 8.0	15.0	0.109	11.2	0.616	97.1	0.617

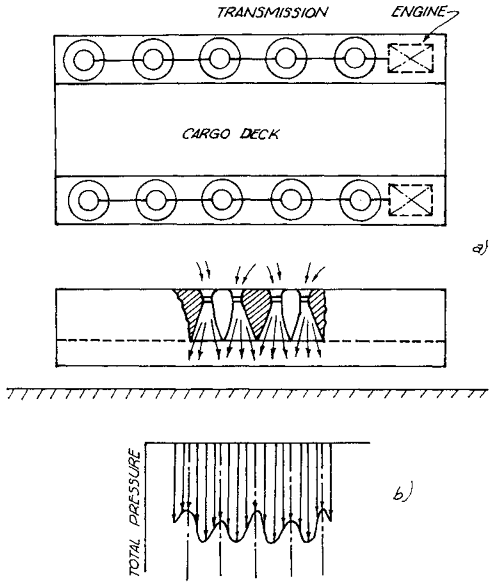


Fig. 6 Walker's suggestion for a multiplicity of axial fans mounted at the edge of a GEM.

Most generally, some form of base compartmentalization must be introduced as well, usually in the form of one or more central air jets. These are usually regarded as wasted energy, since they contribute little lift. Some vehicles dissipate as much as 20% of their total lift power on auxiliary jets of this type.

In forward flight there is also the problem of pitching moment, as indicated in Fig. 5. If we achieve 100% recovery of ram pressures in the jets, a nose-up couple $HU_0\dot{m}$ will act on the vehicle, $\dot{m}$ being the total mass flow. For less than 100% ram recovery, the couple will be less, but if the intake is high, the moment will be approximately the same. Obviously the most powerful way of reducing this effect is by reducing the value of H by reducing the height of the intake.

Peripheral Fan Concept

Peripheral fans provide an elegant solution to many of these problems by eliminating most of the duct loss and cross-flow effects. An early suggestion by N. K. Walker was the multiplicity of axial fans sketched in Fig. 6. The obvious

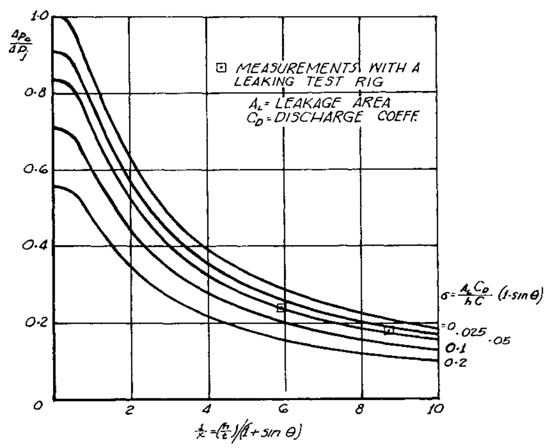


Fig. 7 Effect of leakage on the cushion pressure of an annular jet GEM.

disadvantage with this approach, apart from transmission weight and complexity, is the series of "holes" introduced into the jet curtain, as indicated in Fig. 6b. To obtain an idea of the losses involved, we might guess that the total "hole area" could be 10% of the curtain area. Then, from Fig. 7, taken from Ref. 5, the cushion pressure loss would be about 40%. Thus the efficiency of the system would be the same as for the conventional approach, whereas the weight and complexity would be increased.

The ideal peripheral fan would involve no increase in mechanical complexity and would be continuous around the periphery of the GEM. If we represent the means of imparting energy to the air by an actuator surface (following Froude), then a cross section of the ideal system would be as sketched in Fig. 8.

Apart from saving the 50% duct loss of a conventional annular jet, it is evident that such an installation 1) can reduce drag by cleaning up the wake in a manner analogous to boundary layer suction, 2) can increase aerodynamic lift by giving a greater degree of "mound flow" (Ref. 9 shows that it is possible to approach double the lift by this means), 3) can possibly recover, via recirculation, some of the front jet energy, and will have nearly 100% ram recovery, 4) will reduce the size of any separation bubble over the leading edge at low speeds, 5) will reduce nose-up pitch because the height difference between jet and intake is a minimum, 6) will

Table 2 Efficiency of some existing GEMS: annular jet vehicles, from Ref. 3

Company	Model	Planform, ft	W	bhp/W	h	C	A_l	Δp_c	hC/A_c	$(2\Delta p_c/\rho)^{1/2}$	$\frac{P_F/W}{(2\Delta p_c/\rho)^{1/2}}$
Aerophysics[a]	GEM II	35.3 × 29.7	25,000	0.0296	8.0	130.0	1048	23.85	0.0828	141.5	0.115
AVRO, Canada[a]	Avrocar	18.0 diam	5,600	0.536	36.0	56.6	254	22.0	0.669	136.0	2.17
Bertelson[a]	Aeromobile 200	16.0 × 8.0	2,200	0.091	12.0	48.0	128	17.18	0.375	120.0	0.417
Britten-Norman	Cushioncraft	19.0 diam	3,000	0.0566	15.0	59.6	284	10.55	0.262	94.2	0.331
Curtis	ACM-2-2	21.0 × 8.0	3,460	0.0867	9.0	58.0	168	20.6	0.259	131.5	0.363
Curtis	ACM-6-1	21.0 × 8.0	3,260	0.092	6.0	58.0	168	19.4	0.0725	127.7	0.397
Fletch-Aire	Glidemobile	14.2 × 5.5	471	0.152	4.0	39.4	78	6.04	0.1682	71.2	1.172
Gyrodyne	55	9.2 × 6.0	795	0.0818	6.0	30.4	55	14.45	0.2762	110.0	0.409
Saunders-Roe	SR-N1	30.0 × 25.5	11,200	0.0402	8.0	111.0	765	14.63	0.0966	111.0	0.199
Saunders-Roe[a]	SR-N2	63.0 × 29.5	50,000	0.064	12.0	185.0	1860	26.85	0.0994	150.2	0.235
N.R.A.	GEM I	14.6 × 8.2	1,100	0.0726	14.0	45.6	120	9.16	0.443	87.8	0.455
N.R.A.[a]	GEM III	24.0 × 12.0	2,000	0.070	15.0	72.0	288	6.95	0.3125	76.5	0.503
Princeton	X-3	20.0 diam	1,070	0.0449	14.0	62.8	314	3.41	0.233	53.6	0.46
Princeton	X-3B	20.0 diam	1,600	0.1125	24.0	62.8	314	5.1	0.400	65.5	0.945
Princeton (Flex skirt)	X-4	9.0 diam	400	0.0375	3.0	28.25	64	6.25	0.1103	72.5	0.284
Princeton (Flex skirt)	X-2	8.0 diam	300	0.0167	5.0	25.1	50	6.0	0.2095	71.0	0.129
Vickers	3031	47.5 × 20.1	16,500	0.0606	18.0	135.2	955	17.28	0.212	120.5	0.277
Weiland	ILEN	33.0 × 30.0	16,420	0.0439	16.0	126.0	990	16.6	0.1697	118.0	0.204

[a] Demonstrated performance.

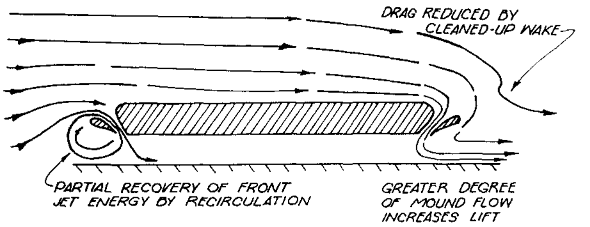


Fig. 8 Idealized peripheral fan GEM in forward flight.

eliminate internal crossflow during a pitch or roll perturbation, thus increasing the static stability derivatives and reducing the horizontal force that couples angular and translational motion, and 7) avoids the need for a complicated central structure and allows the payload to be carried near the center of the GEM; this aspect is a great deal more important than might be thought at first sight. All of these advantages are potentially important, but the outstanding characteristic, namely, halving the power loss due to ducting, is of course of pre-eminent importance. In practical terms, this means the gross weight can be increased in the ratio $2^{2/3} = 1.59$ for the same performance, so that the payload increase can be as much as 100% if the peripheral fan installation is no heavier than the system it replaces.

Some Typical Peripheral Fan Installations

Circular Planform with an Axial Fan

The vehicle illustrated in Figs. 9 and 10 is completely conventional in that it has axial fan blades, the performance of which is well understood and easy to calculate. The most obvious drawbacks to such an approach, at least in the larger sizes, are the necessity for a circular planform and the problems associated with torque reaction. This is certainly the most efficient configuration possible using conventional techniques; however, with optimum jet thickness and angle, its system efficiency can theoretically approach 80%, that is to say, twice the efficiency of the best current GEM. Gear box and transmission weights will be very considerable in the larger sizes, however, since the maximum peripheral speed of the fan is limited to about 500 fps by practical considerations.

The Frost MSHC GEM of Fig. 1 is also a member of this family, but with a very thick (half the diameter!) nonuniform jet, as indicated in Fig. 11. The fact that it is only 40% efficient is attributable to the following reasons.

1) The optimum value of the height parameter

$$x = (t/h)(1 + \sin\theta)$$

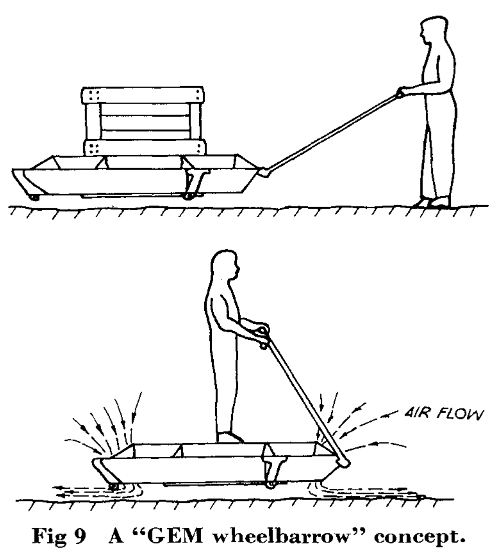


Fig 9 A "GEM wheelbarrow" concept.

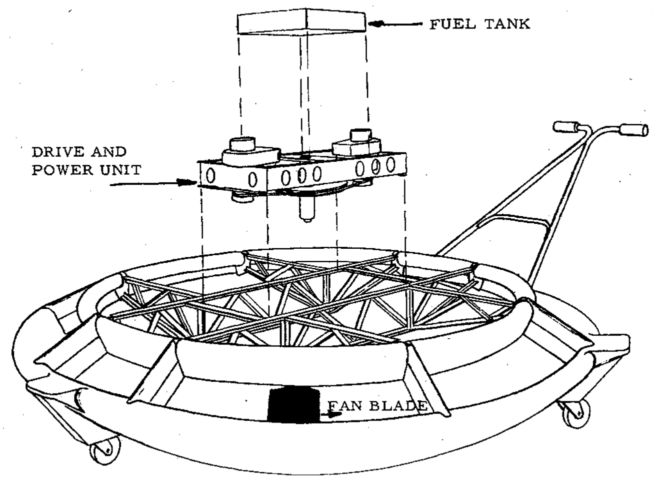


Fig. 10 Structural details of the Frost peripheral fan "wheelbarrow."

is $x = 1.45$, as shown in Ref. 1 (where the values of $x = 1.0$, derived from "thin jet" theory, and 0.7, from layered jet theory, are shown to be in error). For the MSHC, $x \simeq 0.2$, and so it is very far from optimum.

2) The stators that compartmentalize the base and straighten out the fan airflow are rectangular in section, instead of aerofoil shaped, and are mounted at zero incidence in the interests of structural simplicity. Thus the resulting flow separation causes a pressure loss.

3) A significant fraction of the total air mass flow is diverted for engine cooling, and thus does not contribute to lift. This could have been avoided if we had felt justified in spending the money to develop an exhaust eductor cooling system.

4) The total pressure distribution across the "jet" is not uniform. There are reasons for believing that total pressure should be a maximum over the inner portions of the jet; it is obvious from Fig. 9 that the MSHC GEM goes the other way.

Rectangular Planform with a Crossflow Fan

The crossflow fan illustrated in Fig. 12 rotates about a horizontal axis so that it can be used in conjunction with a rectangular planform. Although the first crossflow fan patent is credited to the Frenchman Mortier in 1892, it is still a relatively unusual concept, and our predictive ability is not as far advanced as we could wish. Reference 6 contains a theoretical analysis of this system, and shows that the pressure rise through the fan occurs partly as it enters the fan drum (the upper half of Fig. 13) through the aerodynamic reaction of the cascade of aerofoils, and partly through centrifugal pumping as it leaves the drum with a swirl velocity equal (approximately) to the fan tip speed. The relative contributions of these two effects are illustrated in Fig. 14.

As shown in Fig. 15, the installation of such a fan in a GEM is easy to visualize. The required rotational speed is fortunately comparable with practical power plant shaft speeds, so

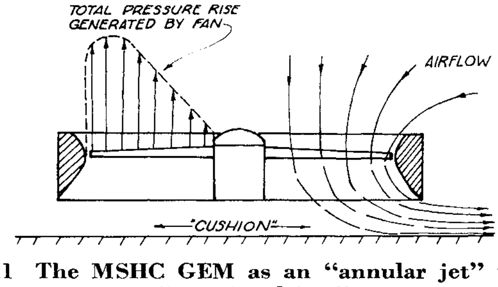


Fig. 11 The MSHC GEM as an "annular jet" with a "peripheral fan."

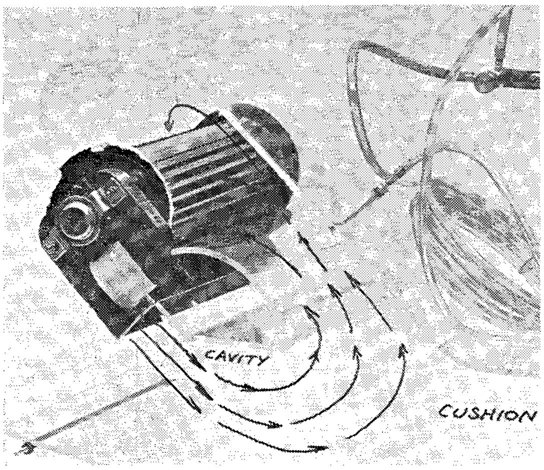


Fig. 12 Typical "crossflow" fan in a recirculation test rig. The arrows show the direction of air flow.

that torques are low and there is no need for large gearboxes. Torque reaction is not a problem at all, of course, because of the direction of rotation.

By differentially varying the exit area, we achieve a powerful method of control in pitch and roll, whereas either collective variation or control of the fan speed gives heave control. It is found that this type of installation also gives improvements in ability to handle offset loading cases. Unfortunately no information is available which would permit the prediction of crossflow fan weights in the large sizes necessary for GEM use.

Rectangular Planform with a Constant Displacement Fan

The axial and crossflow fans so far considered deliver roughly constant total pressure up to their stall points (Fig. 16), so that their mass flow and momentum flux decrease as the back pressure increases. A constant displacement fan, on

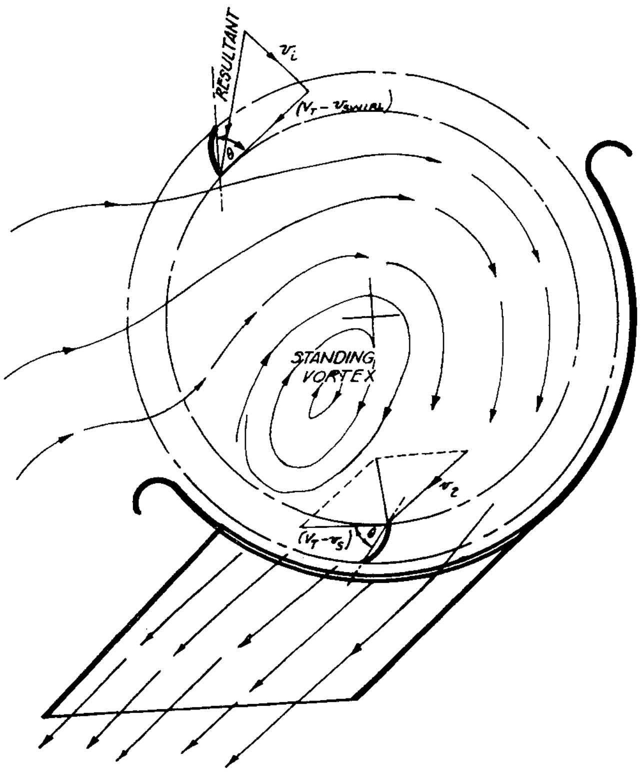
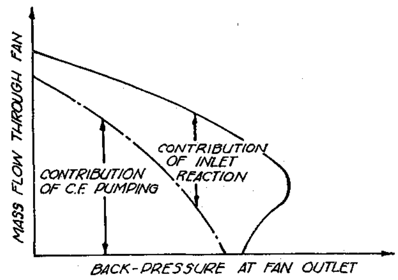


Fig. 13 Transverse flow fan geometry.

Fig. 14 Calculated performance of a crossflow fan.



the other hand, delivers its appropriate quota of air irrespective of the back pressure, at least until leakage of the air past the blades becomes important. Thus a GEM with this type of fan is likely to be stiffer in heave and angular displacements and better able to react off-center conditions. It should also have more damping as indicated in Fig. 17.

One development along these lines is the "frost fan" illustrated in Fig. 18, which has been employed in test rigs for both annular jet and recirculation configurations.

The efficiency of this type of fan depends very much on the friction of the rollers, which the blades use to track the case, and upon the leakage area between the blades and the case. Because of insufficient appreciation of the leakage effect when designing the test models, and because the rolling friction coefficient turned out to be 0.04 instead of 0.01, the highest efficiency that we achieved experimentally was 55%. Agreement with the theory developed was very good indeed, however, so that we have no hesitation in predicting a figure of 80% for future fans. A typical predicted efficiency curve is given in Fig. 19.

As may be imagined, blade dynamics are very important in this type of fan, and minimizing the blade tip loads and internal stresses requires very careful design. We have been through four different blade designs in an effort to reduce weight, and are now looking at the quite different approach of completely flexible blades portrayed in Fig. 20, where the tip roller friction loss and end-leakage losses are also avoided by the use of rotating end bells.

In general, the points in favor of the constant displacement fan are the same as for the crossflow fan, except for the additional advantage of constant mass flow and therefore of momentum flux. There is some reason to believe that it can be made more rugged and "bullet proof," and of course it does not have the crossflow fan's severe blade-bending problem due to centrifugal force. However, it is too early to make an informed decision between these two alternatives at the present time, particularly since no weight analysis studies have been carried out for either concept.

Arbitrary Planform with Peripheral Eductors

An eductor is a little-understood device of extreme conceptual simplicity and considerable aerodynamic complexity, which is capable of multiplying the mass flow and momentum flux of a primary jet. Its important elements are indicated in Fig. 21.

In Ref. 7 the writer has developed a theory of eductors which gives good agreement with experiment, in contrast to

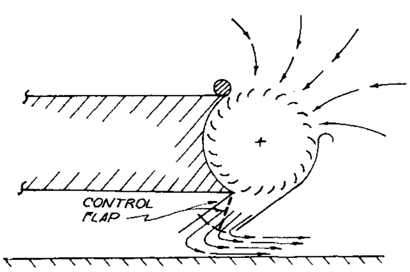


Fig. 15 Crossflow fan installed in a GEM.

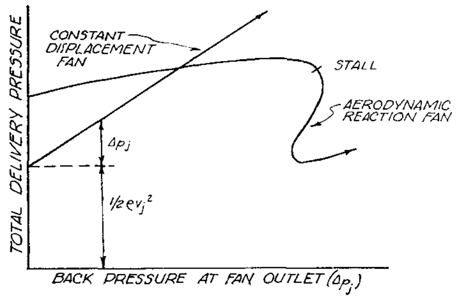


Fig. 16 Total pressure delivered by reaction and constant displacement fans.

the rather optimistic predictions of previous theories. It is shown that the absolute maximum thrust augmentation cannot exceed

$$(J_2/J_a)\,|_{\max} = [\eta_D/(1 - \eta_D)]^{1/2}$$

where η_D is the diffuser efficiency based upon the throat dynamic head. This result is plotted in Fig. 22, which emphasizes the key to successful augmentation, i.e., the achievement of high diffuser efficiencies.

Without going into the analytical details, it is possible to show that, in incompressible flow, the thrust augmentation of an "optimum static eductor" (which has ambient pressure upstream and downstream) is

$$\frac{J_2}{J_a}\bigg|_{\text{static}} = \frac{(n + 1)\eta_D^{1/2}}{\Delta\bar{P}_j[(n + 1)^2 - n^2\eta_D]^{1/2}}$$

The effects of the upstream total pressure (ΔP_c) and the exit static pressure (Δp_2) being greater than ambient appear as Southwell coefficients to this basic equation. In this equation,

n = ratio of entrained to primary air mass flow
η_D = diffuser efficiency, based on throat dynamic head
$\Delta\bar{P}_j$ = $\Delta P_j/\frac{1}{2}\rho v_j^2 = \Delta P_j/[1 - (\Delta p_1/\Delta P_j)]$
ΔP_j = (gage) total head in the primary jet
Δp_1 = static pressure in the mixing section
J_2 = total augmenter momentum flux
J_a = momentum flux of primary jet when exhausting to ambient

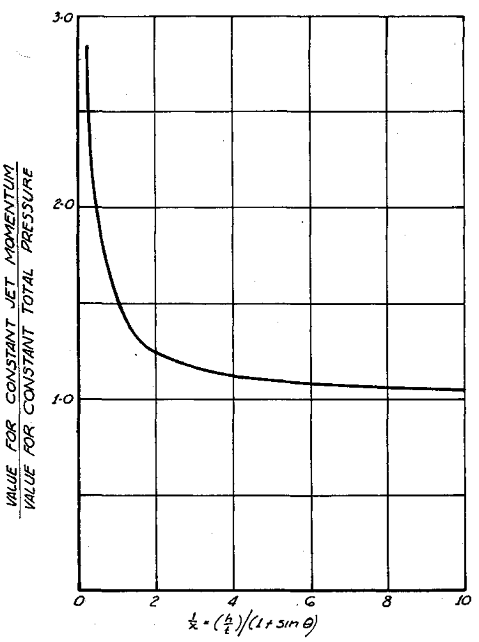


Fig. 17 Damping and heave frequency ratio for constant mass flow vs constant total head peripheral jets.

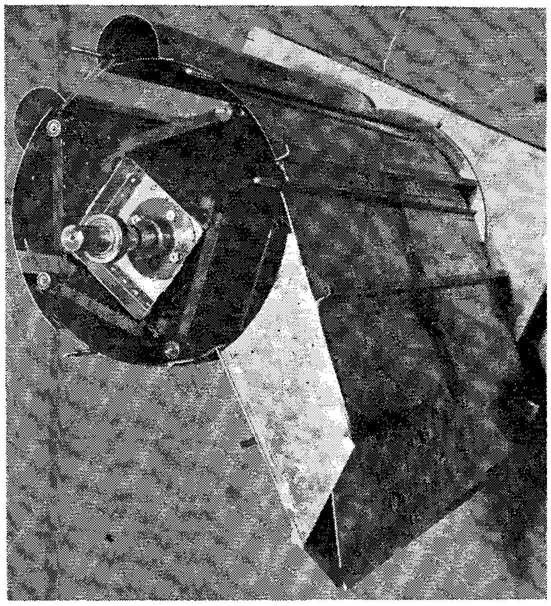


Fig. 18 A full-scale "Frost fan" with one end-bell removed.

Modern gas turbine technology has made compressed air a commodity that is very easy to obtain in large quantities, and at very low powerplant weights. Thus, although an eductor is not a "fan," this paper would be incomplete without noting its applicability to GEM's.

A typical installation is portrayed diagramatically in Fig. 23. In this case we have indicated a "streamline diffuser" with either boundary-layer suction or pressurization at the points x–x, which should enable a diffuser efficiency of about 97% to be achieved. Another approach is the centrifugal diffuser, where the wall curvature gives rise to centrifugal forces, which just balance out the pressure rise due to diffusion (resulting in zero pressure gradient on the wall), the pressure recovery being reacted on stators at the diffuser exit plane.

It is important to realize that even with zero augmentation such a system would be competitive with a conventional annular jet machine, thanks to the very low system weight: an aspect which is well illustrated by Cossairt in his studies of eductor-driven recirculation at Martin-Orlando (Ref. 8, for example). Thus by achieving an augmentation of two or three

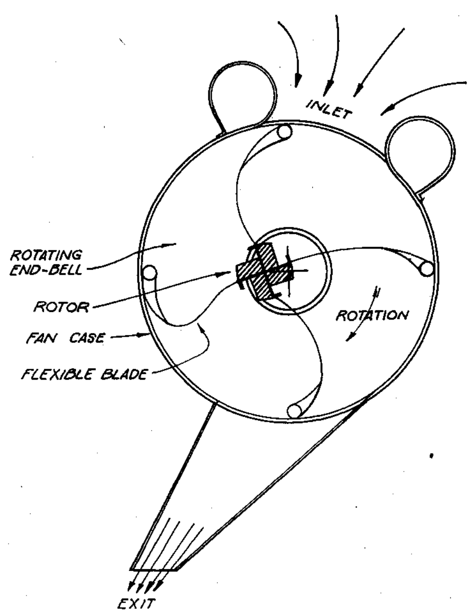


Fig. 19 A constant displacement fan concept with flexible blades and rotating end bells.

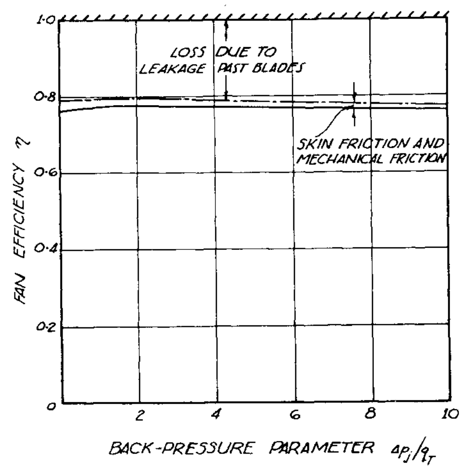


Fig. 20 Measured efficiency of a full-scale "Frost fan" corrected to zero roller friction.

we have a system that can potentially give us a major improvement in operating economics with the added bonus of a substantial reduction in mechanical complexity.

The eductor can also be applied to GEM's in a more conventional way, of course, such as pumping up a plenum chamber.[10]

Appendix: System Efficiency of a GEM

In this appendix we use the following symbols:

A_c = cushion area, ft²
C = circumferential length of jet curtain, ft
P_j = air power in jet = $\frac{1}{2}\dot{m}_{Ja}v_{Ja}^2$, lb-ft/sec
P_F = shaft power input, lb-ft/sec
h = height above the ground-plane, ft
Δp_c = cushion pressure, psf
W = total weight of GEM, lb
η = system efficiency
ρ = mass density of air, slugs/ft³

A relationship can be established which enables the system efficiency (η) of any GEM configuration to be established from experimental measurements of lift and shaft power input, relative to an ideal, optimized annular jet machine. If the jet momentum flux is small in relation to the cushion force and the curtain area is less than half the cushion area, then a simple equation can be derived to give η in terms of cushion pressure and shaft power only.

Using this approach, an annular jet that had fan and duct efficiencies of 100% would still have a system efficiency of less than 100% unless its jet thickness and angle were optimum. However, since we assume a uniform total head distribution across the jet nozzle, there probably exist total head distributions that would give an efficiency in excess of 100%. Also, since the derivation is based upon "exponential theory," it suffers from the appropriate limitations of the theory.

A fundamental performance parameter of a GEM is

P_j/W = jet power in ft-lb/sec/weight lifted in lb

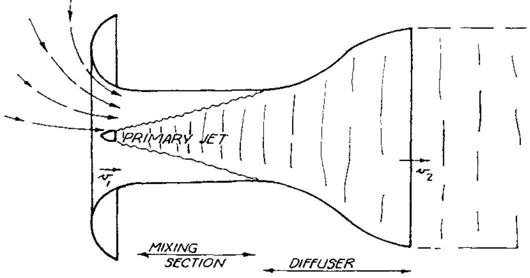


Fig. 21 Eductor geometry.

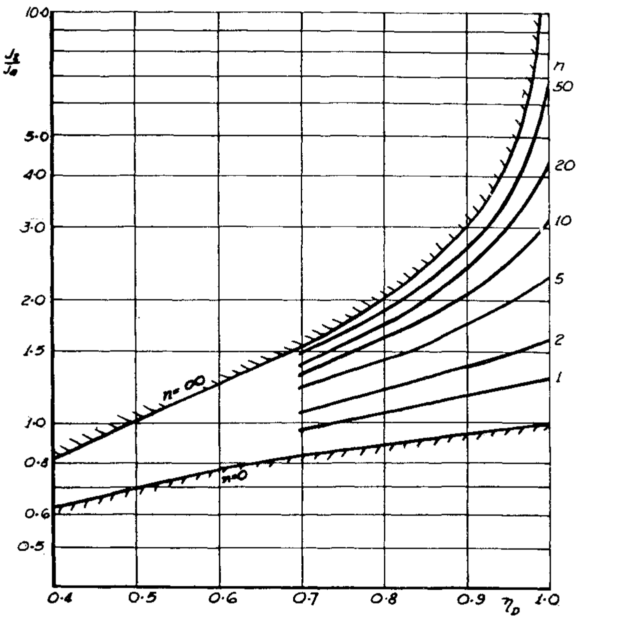


Fig. 22 Static eductor augmentation as a function of mass flow ratio (n) and diffuser efficiency (η_D).

Performance theory is most highly developed for the annular jet configuration, and it is therefore logical to use the performance of an optimum annular jet as the base for comparison of other systems.

From Ref. 2, the optimum height parameter (x = 1.45) and optimum $\theta(= \tan^{-1}A_c/hC)$,

$$\left.\frac{P_j}{W}\right|_{\text{opt}} = \left.\frac{\eta P_F}{W}\right|_{\text{opt}} = \frac{0.81(hC/A_c)[(2/\rho)\Delta p_c]^{1/2}}{1 + [1 + (hC/A_c)^2]^{1/2}}$$

This equation is plotted in Fig. 2. The actual power required will be the value given by the equation divided by the system efficiency η, which must account for all duct losses, in addition to the efficiency of the fan(s). For typical annular jet GEM's currently in existence, η = 0.1 to 0.4.

If we superimpose experimentally determined values of $(P_F/W)/[(2/\rho)\Delta p_c]^{1/2}$ upon Fig. 2, the ratio of the experimental value to the theoretical curve at the same value is the relative system efficiency. When the jet momentum flux can be neglected in relation to the cushion lift force ($A_c\Delta p_c$),

$$\left(\frac{P_j}{W}\right)\left(\frac{\rho}{2\Delta p_c}\right)^{1/2} = \frac{P_j}{A_c\Delta p_c}\left(\frac{\rho}{2\Delta p_c}\right)^{1/2}$$

a relationship that is useful in reducing test rig data. If $hc \ll A_c$ also, then it can be shown that

$$(P_j/\Delta p_c)(\rho/2\Delta p_c)^{1/2} \simeq 0.405hC$$

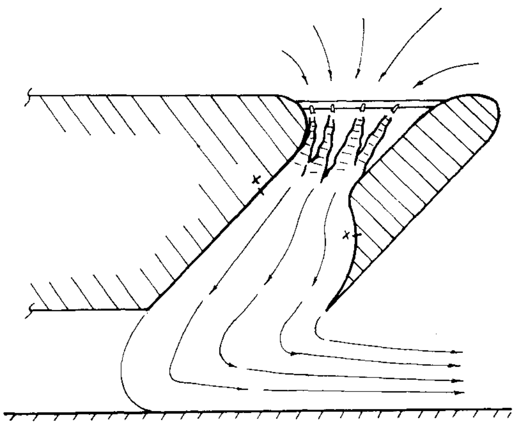


Fig. 23 Peripheral eductor installation.

so that

$$\eta \simeq 0.405 \left(\frac{W}{P_F}\right)\left(\frac{hC}{A_c}\right)\left(\frac{2\Delta p_c}{\rho}\right)^{1/2}$$

where P_F is the shaft power input. Within the constraints specified, this equation can be used to reduce test rig data. It can of course be applied to any type of GEM configuration.

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