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WIND LOADING ON TRACKING AND FIELD MOUNTED SOLAR COLLECTORS

L. M. MURPHY

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Solar Energy Research Institute
A Division of Midwest Research Institute

1617 Cole Boulevard
Golden, Colorado 80401

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L. M. Murphy

Solar Energy Research Institute
1617 Cole Blvd.
Golden, CO 80401

ABSTRACT

In developing solar collectors, wind loading is the major structural design consideration. Wind loading investigations have focused on establishing safe limits for steady state loading and verifying rational, but initial and conservative, design approaches for the various solar collector concepts. As such, the effort has been very successful, and has contributed greatly to both the recognition and qualitative understanding of many of the physical phenomena involved. Loading coefficients corresponding to mean wind velocities have been derived to measure the expected structural loading on the various solar collectors.

This paper, which is an outgrowth of a larger study (1), discusses current design and testing procedures for wind loading. The test results corresponding to numerous wind tests on heliostats, parabolic troughs, parabolic dishes, and field mounted photovoltaic arrays are discussed and the applicability of the findings across the various technologies is assessed.

One of the most significant consistencies in the data from all of the technologies is the apparent benefit provided by fences and field shielding. Taken in toto, these data show that load reductions of three, or possibly more, seem feasible, though a more thorough understanding of the phenomena involved must be attained before this benefit can be realized. It is recommended that the required understanding be developed to take advantage of this benefit and that field tests be conducted to correlate with both analyses and tests.

NOMENCLATURE

A	area (m^2)
C	force or moment coefficient
d,h,l',l,w	characteristic lengths (m)
n	exponent corresponding to different terrains
q	dynamic pressure (P_a)
u	velocity (m/s)
x,y	coordinates
z, z_o	heights above ground (m)
α	pitch angle
β	yaw angle

SUBSCRIPTS

D	drag
L	lift
M	moment
O	reference datum

INTRODUCTION

Wind loading, especially on a structure with a large, exposed surface area, is a crucial design factor. Historically, wind loading has been an important concern in the safe construction of buildings and bridges. An excellent documentation of this field is presented in Refs. 2,3. Understanding of wind loading and designs to withstand that loading have evolved rapidly in the last 30 years or so, permitting the design of structures with a high assurance of safety. More recently, cost effectiveness and methods to optimally withstand windload have been the focus of much research.[1] To meet cost

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[1] Reference (4) notes that more than 5000 papers have been published on wind forces since 1970.

goals, new construction methods have resulted in lighter, more flexible structures with reduced damping. These new structures require an even greater understanding of wind loading to simultaneously guarantee structural integrity and economy as well as safety.

During the last five years, wind loading on solar collectors has been the subject of much concern and investigation. Safety problems associated with the potential collapse of bridges and buildings along with the likely attendant loss of life are not present. However, concern for protecting the frequently large capital investment of these systems is a priority, as is the need to meet stringent energy collection performance requirements. This has been especially true for tracking and other field-mounted collectors, where low cost and reliability for these repetitive structures are required. The effects of wind loading on these structures have been shown to be more severe than those caused by snow, rain, weight, earthquakes, thermal expansion, or any other environmental condition.

Wind forces are difficult to model for a tracking collector because the collector moves. Besides having to safely sustain maximum expected loads, a tracking collector must also be able to maintain its desired orientation within a certain accuracy band in typical wind environments and at minimum cost. Further, the weighting of these factors--survival or pointing accuracy--varies, depending on the needs of the specific collector.

Another area receiving considerable attention is photovoltaics, where large field arrays of nontracking collectors are being proposed for central generation concepts.

Finally, loading on flat-plate nontracking collectors for heating and cooling applications has been the focus of a recent detailed study (5). Wind loading on these collectors, which are usually mounted on buildings (though ground mounting is not rare) has typically not been a major concern. This is because the support structures for these applications are routinely overbuilt. However, concern for ensuring the integrity of glazings has arisen, and recent findings have shown that support structures and mounting can lead to substantial costs, especially if additional roof reinforcing is required.

Wind loading on heliostats, parabolic troughs and dishes, and large-scale nontracking photovoltaic arrays are discussed in this paper. The function of these concepts and their specific applications are discussed in many references (6,7,8,9), and schematics are shown in Fig. 1 of each collector concept. The four technologies not only have different design philosophies, but their various physical and deployment configurations lead to different loading conditions for similar wind speeds.

CURRENT DESIGN APPROACHES

The most comprehensive (albeit at times conservative) design approach for wind loads used in the United States is ANSI A58.1-1972 (10)[2], developed by the American National Standards Institute. It was developed by a consensus approach and includes current practices, engineering knowledge, past experience, and synthesized research knowledge in the field. It is supported by extensive professional review and agreement and, as such, carries more weight than other kinds of standards. The ANSI standard has been adopted by the National Building Code in its entirety, but other U.S. building codes adopt only parts of it or other older standards (11).

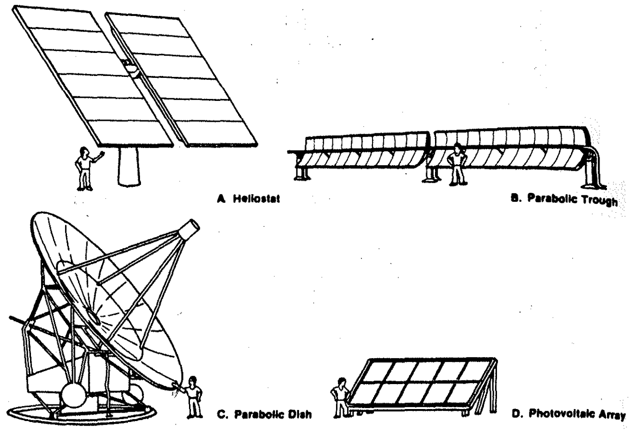

Figure 1. Typical Configurations Corresponding to Various Solar Collector Concepts

The ANSI standard is a good starting point for designing solar collectors; however, strict application and adherence to it leads to several difficulties. First, the code (in its present form) states that the standard does not apply to structures of unusual shape. Next, since most of the standard was based on concern for life and safety rather than economic issues, the code is quite conservative (10). Other indications of conservatism in the standard are that the wind velocity for elevations less than 10 m (33 ft) is assumed to be constant and equal to the velocity at 10 m, and that a 100-yr recurrence interval is recommended where life and safety are major issues. A 25-yr recurrence interval is recommended where safety is not a primary issue. Further,[3] the standard recommends designing for wind loading corresponding to the full approach flow, since load reductions due to shielding by other adjacent structures is not allowed. Wind tunnel data which addresses both shielding and channeling effects is allowed to supplement the code for special cases; however, specific guidelines in the generation of the data and its use are not given. The coefficients in the current standard appear somewhat conservative since most of them were obtained in smooth flow wind tunnels rather than in boundary layer tunnels (i.e., tunnels in which the

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[2] This standard is currently under revision (12). Modifications are suggested not only by standards committee members, but also by groups addressing particular issues of interest to industry (13).

[3] In a recent proposed form of the ANSI standard now under consideration, considerably more boundary layer wind tunnel data is used, and specific guidance for wind tunnel testing is given (12).

expected natural boundary layer profile is modeled) (11). Thus, additional procedures are needed in the design of solar collectors for wind loading.

Technical guidance for solar collectors from the national laboratories (since the vast majority of wind-related collector development is federally funded) has allowed significant flexibility in design procedures. Basically, the recommended approach combines information and guidance contained in the ANSI standard with supplemental information from wind tunnel data on an individual or case-by-case basis. The biggest problem facing collector developers has been that little wind loading data and knowledge specific to solar collectors has been available. Hence, to speed collector development, and to take into account data as it becomes available, the national laboratories have used an iterative, and interactive, consensus approach to evolve a set of "best estimates" of expected wind speeds to use for design purposes. Although there has been considerable interaction between the laboratories and the contractors involved within a particular solar technology, limited interchange across solar technology development has occurred. A common reason given for this apparent lack of coordination has been that each application is unique. This is a valid perspective, especially in the initial development stages. However, sufficient information is now becoming available that will assist all solar technologies. Table 1 shows critical design wind speeds currently being recommended for design purposes.

It should be noted that the various solar technologies have different design requirements and philosophies. For instance, survival in high winds is always an issue, but deformation under loading is a major concern with heliostats and dishes. In fact, for heliostats the high stiffness requirements to maintain the appropriate orientation usually result in a structure that can easily survive the worst storm condition in the stow configuration. With trough collectors, the pointing accuracy requirements during operation are more than an order of magnitude less than those for heliostats, and the controlling design condition is survival. With parabolic dishes, both pointing accuracy and survival appear to be equally crucial design drivers, but at the present the slew-to-stow condition is the major concern.

The bulk of the wind loading data gathered for the various solar technologies has focused on the most fundamental problem first; i.e., that of determining the loading induced by mean wind velocities. Structural and dynamic interaction problems have not been central in any of the numerous U.S. experimental studies; nor has the effect of gusts. However, as the need arises, the more complex dynamic problems are expected to be addressed in future work. A discussion of previous wind-loading studies follows.

METHODS OF DETERMINING WIND LOADING

Analytical work on bodies in airflow fields has been very limited, dealing mainly with simple geometric configurations and relatively low flow rates and corresponding Reynolds (Re) numbers. This is because of the complexities of turbulence and its interaction with the structure. Thus, most work on airflow has been highly empirical. Unlike the aerodynamics of streamlined bodies, which is highly developed for aeronautical applications, the aerodynamics of bluff bodies in turbulent shear flows involves the nonlinear interaction of nonhomogeneous, nonuniform, turbulent approach-flow with three-dimensional turbulent boundary layers and separated flows over the body. None of these complex flow types is well described even when unperturbed by the others (3). Therefore, due to the number of variables, the results of a particular study are difficult to generalize; thus, many studies are often needed to characterize all of the operative phenomena.

To date, considerable combined analytical and testing work on airflows around bluff bodies and flat plates in two dimensions has been done. More recently, data collection and analysis for complex three-dimensional flows has recently been directed

Table 1. CRITERIA CURRENTLY IN USE FOR THE DESIGN OF SOLAR COLLECTORS

Collector Technology	Heliostats[a]	Troughs[b]	Dishes[c]	Photovoltaic[d] Arrays (Nontracking)
Maximum survival wind speed, m/s(mph)	(stowed) 40 (90)	(stowed) 35 (80)	(stowed) 44 (100)	Based on 100-yr mean recurrence at site
Design wind speed for normal operation, m/s (mph)	12 (27)	11 (25)	16 (36)	Based on 25-yr mean recurrence at site
Maximum wind speed during which collector must track, m/s(mph)	22 (50)	22 (50)	16 (36)	Not applicable
Stated or implied mean recurrence internal, yr	100 (extreme)	25 ground mounted 50 roof mounted (extreme)	100 (extreme)	25 (operating) 100 (extreme)

[a] Reference 14.
[b] Reference 15.
[c] Reference 16.
[d] Recommendation in Reference 17.

at solar collectors (6,18,19,20). Experimental analyses have focused on a range of sizes from 1/60-scale to full-scale tests. The results of these analyses will be discussed below.

Data Presentation

In either full-scale or model experimental studies, data is usually taken so that loadings can be expressed in terms of force coefficients defined by

$$C_{FORCE} = \frac{FORCE}{qA}$$

$$C_{MOMENT} = \frac{MOMENT}{qA\ell} \quad , \qquad (1)$$

where $C_{( )}$ is appropriate force, the coefficient, q is the "dynamic pressure," A is an appropriate area, and ℓ a characteristic length. The dynamic pressure q may be expressed by

$$q = \frac{1}{2} \rho u^2 \quad ,$$

where

ρ = mass density of air stream [equal to 1.225 kg/m^3 (0.00238 slugs/ft^3) under standard conditions]

u = velocity.

Any consistent set of definitions may be used for A and ℓ. For example, an acceptable set of definitions is

	Heliostat	Trough	Dish
ℓ	Collector Height (h)	Collector Aperture Width (C)	Principal Dish Diameter d
A	h • Collector Width (w) = h • w	C • Collector Length (l') = C • l'	$\frac{\pi d^2}{4}$

Because of excessive costs (associated with both the systems and components being tested as well as the scope of the available facilities), the use of subscale or model tests, from which the loads on the full-scale device can be inferred, is dictated. This can be done by using the laws of dynamic similarity and simulating the natural boundary layer winds in a wind tunnel in which the force coefficients would be identical for the model and prototype. Hence, in a valid simulation, results of the test can be scaled to the full-sized prototype by simply inverting Eq. 1. Thus,

$$\text{Force (Prototype)} = C_{FORCE}qA$$

$$\text{Moment (Prototype)} = C_{MOMENT}qA\ell^4 \qquad (2)$$

Modeling

Modeling is at best an approximation to reality since all of the phenomena that are operative cannot be simulated simultaneously. Thus, those aspects of the process that have the dominant effect on the system of interest are modeled most closely.

Accurately modeling the boundary layer requires that the vertical flow distribution and the turbulence intensity and spectrum in the wind tunnel match those at the site and that the Reynolds number (Re) of the model and the prototype be equal. In addition, the scale model must be geometrically similar to its prototype. If structural dynamic responses are to be modeled, structural stiffness (or elastic) similarity must also be maintained. A more detailed discussion of these requirements and their implementation in the wind tunnel environment is found in numerous references, such as (3). The difficulties in modeling all parameters are great, and compromises are often necessary. Further, there are relatively few[5] wind tunnel facilities capable of modeling the natural boundary layer winds at a specific site. There are, however, a significant number of facilities capable of performing aerodynamic loading on specific structures where the specific boundary layer structure is not important and only approximate total loads are required.

Usually the vertical velocity distribution profile is modeled fairly closely. The vertical velocity profile can frequently be represented by a power law relation between the velocity u at a height Z and a reference velocity $u(z_o)$ at a reference height z_o:

$$u(z) = u(z_o) \left(\frac{z}{z_o} \right)^{1/n} \quad ,$$

where n is an exponent dependent on the local terrain roughness and other effects such as buildings or trees. The reference height z_o is usually taken to be 10 m (~33 ft), the height at which much meteorological data is gathered. Most of the boundary layer testing for solar collectors has been done with a profile typical of flat, open terrain (i.e., n = 7).[6] However, variations of this profile have been studied in at least one recent test series (17).

Reynolds number is usually not duplicated in many of the boundary layer wind tunnel tests, and it has never been matched in any of the subscale solar

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[4] Care must be taken in assessing different studies, where the various precise definitions used for the moment arm and points of application must be clearly understood. Care must also be taken that the correct reference velocity is used. Sometimes the collector centerline is used (6,18,21), at times the 10-m (33-ft) height is used (17), and at times the top of the collector is used. For example, using a 1/7 power law for the velocity profile, and typical dimensions for a heliostat of 4.5 m (14.8 ft) for the midpoint, and 8 m (26 ft) for the top, the various drag coefficients expressed in terms of the coefficient at 10 m, $C_D(10)$, would be: $C_D(4.5) = 0.80$ $C_D(10)$ and $C_D(8) = 0.94$ $C_D(10)$. Further, some authors strongly urge the use of a reference height that is associated with the structure, since this procedure tends to remove all effects of mean velocity profile of force or pressure coefficients (see (22)).

[5] Only four facilities in or near the United States are known to the author. These are located at the Colorado State University in Fort Collins, Colo., the Virginia Polytechnical Institute in Blacksburg, Va.,

[6] Typical values for 1/n are 0.28 for wooded areas and suburban locations, 0.4 for urban complexes (23).

tests. This is because the required velocities would be typically too high (e.g., approaching sonic velocities) to be practical (e.g., for a 1/24-scale model, the model velocity would be 24 times the full-scale velocity). However, this is usually not considered important, except possibly in conditions where a curved collector pitches such that the leading edge is close to alignment with the stream. In Ref. 6, it was feared that at this angle the separation point could be strongly Reynolds number dependent, causing lift and pitching moment coefficient errors. This did not prove to be a significant problem with the tests for parabolic collectors, or any other collectors.
CALSPAN, in Buffalo, N.Y., and University of Western Ontario, Ontario, Canada.

Researchers at Colorado State University (3,24) noted that there is usually a diminishing effect when Reynolds numbers exceed 15,000. To put this in perspective, in the full-scale test Reynolds numbers can exceed 10^7, and in the models they are often up to 10^5 (i.e., both significantly above 15,000). In addition, if the flow is extremely turbulent, the Reynolds number dependence is further minimized. Concurrence with this point of view was also reached on a recent heliostat study done in Japan (25). On the other hand, Peglow (19) has shown a possible Re number dependence for the various scaled heliostat tests. His data shows variations of base moment coefficients of 0.62 at $Re \simeq 10^7$ to 0.94 at $Re \simeq 10^4$ (i.e., roughly a 50% increase going from the full scale down to 1/60th scale). There are, however, a number of possible differences that might explain this apparent dichotomy, including large differences in turbulence intensity factor, blockage (3,26) in the tunnel, and the boundary layer within the tunnel. Further, tests done on scale model photovoltaic arrays at different Re numbers show very small differences, but the range may be too small (4×10^4 to 20×10^4) to provide conclusive evidence. Thus, the issue does not appear to be a moot point, and if greater precision is desired than that which is obtainable now, further investigation will be needed.

Turbulence intensity (TI) is defined as the root mean square of the flow velocity variations about the mean velocity (usually assumed to be free stream velocity) divided by the mean velocity. TI is usually expressed as a percentage, and a typical value is 20% (for a 1/7-power boundary layer). The consideration of TI can be important if the variations and distributions of pressure are important. Also, recent experiments on flat circular disks (30) show increases in mean base pressures for increases in turbulence. Further, the CSU people also call attention (17,20,23) to the fact that drag has been reported to increase with increased TI (at constant Re number).[7]

Even though the turbulence integral scale is not modeled exactly in small-scale tests, this may not be a significant problem (17,20), because the difference experienced by the prototype and the model is usually not large. Further, the prototype turbulence is often larger than in the wind tunnel, but the integral scale within the wind tunnel is 2-3 times longer than the model structure being tested.[8] For cases where an upstream collector disturbs the approach flow, differences in TI should result in a diminishing effect, since the local TI will be dominated by the wake characteristics of the upstream object.

Finally it should be noted that wind tunnel tests generally investigate only the characteristics of mean wind loads. Gust effects have been considered to the extent that turbulent structure is adequately modeled. However, dynamic aspects of the response is not modeled, nor are extreme gust loads.

LOADS

Maximum load coefficient data for the various solar configurations, along with classical flat-plate data are compared in Table 2 (with Fig. 2). It is seen that the coefficients vary most for lift and moment. For comparative purposes, the corresponding average drag-induced pressures on the various concepts are shown in Fig. 3, along with dynamic pressure as a function of wind velocity.

The loads corresponding to the maximum uniform (no gradient) velocity flow of air on an individual heliostat (7) agreed with the design code approach such as that given in (2). This same generalization appears consistent with the data on photovoltaic arrays. Limited theoretical analysis (27,28) indicates qualitative agreement, but significant overestimates of the loads occur as applied to photovoltaic arrays. This is due primarily to the inability to predict the correct pressures on the downwind side of the collector, which is in turn believed to be caused by ground effects.

Collector/Field Configuration--Impact on Loads

The following results were demonstrated in the various tests:

- Fences: Fences are, in general, most effective for the nearest rows and provide shielding effects on a magnitude similar to internal array shielding (17,20,29).[9] An excellent discussion of the physical phenomena which occur due to flow over barriers is presented in (27) along with numerous additional references. Porous fences are, in

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[7] It is interesting to note that if TI is held constant, and Re is varied, little or no change in drag is seen.

[8] The turbulence scale and spectrum modeled in the tunnel often correspond to subscales of 200-300. Further, the frequency spectrum during a test will typically correspond to short-duration (i.e., on the order of one hour) wind effects. Synoptic scale effects (i.e., extreme winds occuring once over several days or longer) are not modeled. However the effects of extreme winds can be inferred by using statistical methods with the test data.

[9] Individuals at Sandia (Livermore) have expressed the concern that fences and field protection may not ultimately significantly reduce the survival loads on the heliostats in the stow condition. This is because the heliostats located far from the tower are much more widely spaced than the close in heliostats. Further, the stow configuration offers the least wind resistance and least tendency to break up and mitigate the approaching boundary layer. These effects need more study. Their impact however will not be as significant with troughs, dishes, and fixed photovoltaic arrays.

Table 2. TYPICAL EXPERIMENTALLY DETERMINED MAXIMUM FORCE AND MOMENT COEFFICIENTS FOR VARIOUS INDIVIDUAL SOLAR COLLECTORS SUBJECTED TO WIND LOADING[a,b]

Coefficient	Flat Plate [2]	Heliostat [7]	Trough [6][c]	Dish [8][d]
Lateral Load C_D ($\beta = 0°$)	1.2	1.18	1.44	1.5
C_D ($\beta = 180°$)	1.2	1.0	1.05	1.0
Lift Load C_L ($\beta = 0°$)	0.90 ($\alpha = 155°$)	0.90 ($\alpha = 155°$)	2.0 ($\alpha = 150°$)	0.25-0.30[f]
	-0.90 ($\alpha = 35°$)	-0.90 ($\alpha = 35°$)	-1.2 ($\alpha = 30°$)	-1.4 ($\alpha = 35°$)
Moment Coefficient C_{M_z} ($\beta = 0°$)	-0.12 ($\alpha = 30°$)	-0.21 ($\alpha = 30°$)	-0.30 ($\alpha = 45°, 180°$)[e]	-0.05 ($\alpha = 40°$)
C_M ($\beta = 180°$)	0.12 ($\alpha = -30°$)	0.13 ($\alpha = 30°$)	0.175 ($\alpha = 30°$)[e]	+0.12 ($\alpha = 0°$)

[a] See Fig. 2 for definitions of geometry and force directions.

[b] Moments are taken with respect to the attachment or pivot point, which for simplicity is assumed coincident with the center (in the heliostat case) or the surface apex (in the dish and trough cases). In real hardware cases, there will be some amount of offset, which must be carefully considered. Further, data very often is given for moments at the base of the structure. In this case, the resulting moments from the lift and lateral loads must also be considered. For example, see Ref. 7.

[c] 90° rim angle length/aperature = 3.75.

[d] 75° rim angle, dish depth/diameter = 0.20.

[e] These relatively high values for the pitching moment appear to be caused primarily by combination of boundary layer and ground effects.

[f] See Refs. 4 (pp. 294-295) and 31 (pp. 3-48).

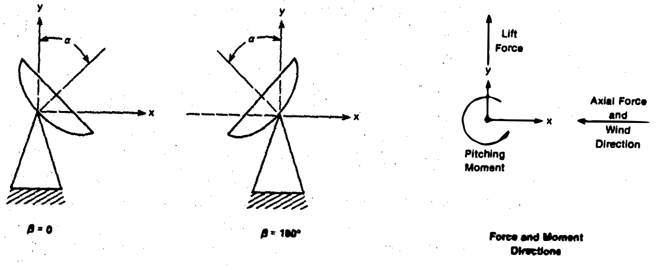
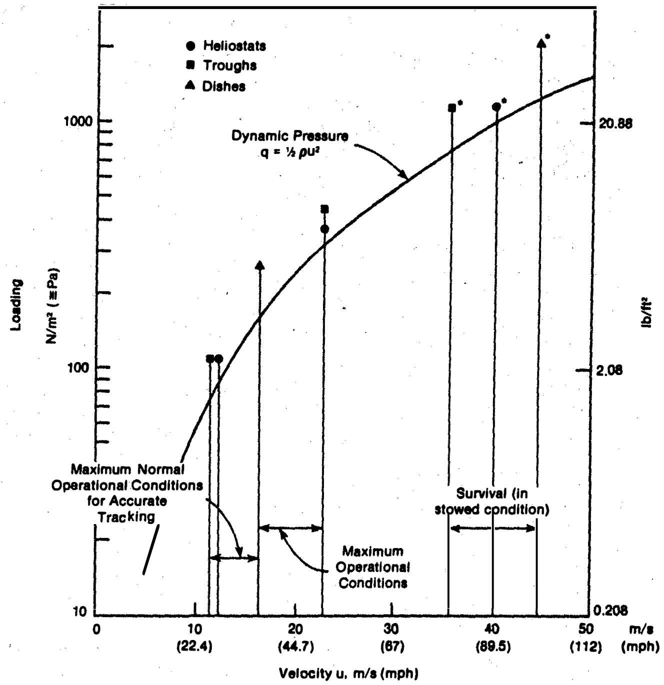


Figure 2. Definition of Geometry and Coordinates Used in Table 1

general, more effective (17,27,28,29) than solid fences; the porosity tended to help break up the vortices behind the fence, and the solid fence at times tended to lift the stream such that the nearest arrays would be located within the vortex behind the fence. A porosity of somewhere between 30% and 40% seems optimal. Fences shorter than the center line of the collector were significantly less effective than higher ones, but few improvements were seen for fences much higher than 0.75-0.90 of the maximum collector height (6,17,27,29) for heliostats, troughs and PV arrays. Fences are less effective for abnormal winds (17) and sharp corners can cause vortex convergence (from the two sides), bringing higher momentum fluxes just inside the fence down onto collectors closest



* These levels are shown for comparative purposes only and should not be reached in practice. In the stowed configuration, the load normal to the collector surface should be much lower.

Figure 3. Typical Dynamic Pressure and Maximum Drag Per Unit Area vs. Wind Speed Showing Typical Collector Design Criteria (Drag Coefficients from Table 1 are used)

to the corners. This problem was eliminated in more recent testing by using fence junctions with less abrupt corners. Also, fences were shown to have some benefit of reducing channeling effects between rows of arrays (29). For heliostats (20,29), pitching moments and drag forces were typically reduced by 50% or more (sometimes up to an order of magnitude). For PV arrays, the effect was somewhat more dramatic; reductions of 60% and more were seen (17). The effect on troughs was similar to that for PV arrays as far as the normal forces go, but moments were not similarly reduced.

- Tilt: The orientations of the various concepts corresponding to the maximum loading conditions are given in Table 3. Normal loads on the collector faces, increase with increasing angle of attack (bluff face windward) to a maximum at a 90° angle of attack (this also corresponds to the maximum drag condition). Also, according to (27), the larger angles of attack tend to increase protection for downwind arrays, by extending the wake regions in which large decreases in steady state flow velocity occur.
- Spacing effects: In general, both the shape and density of the array packing is significant. For heliostats and PV arrays, when arranged in rows, channeling effects were observed (29). In Ref. 20, it was shown that if more than one heliostat obstructs the windward flow, 50% reductions in peak forces and movements were seen. Much less effect was seen when only one heliostat impeded the flow. One very noticeable effect in (29) was that the dense (70% GCR)[10] packing arrangement resulted in significantly higher ground turbulence as compared to the less-dense case (15% GCR). The turbulence intensities were often 60% and 25%, respectively.
- Slots and gaps: Slots and gaps up to 10% porosity in the array itself had minimal beneficial effects on heliostats and PV arrays (20,17). A less than 10% decrease in normal force was seen for a 10% porosity. Gaps had a much greater impact on troughs. A gap of only 6% of the aperture width allowed the collectors to act independently (like an infinite gap). Porosities of up to 50% were investigated for parabolic dishes (8). At this high porosity, a 25% decrease in the peak moment was observed and a 50% decrease in the peak axial force was observed.
- Aspect ratio: The effects of various aspect ratios for heliostats and PV arrays (where aspect ratios of 2, 3, and 4 were tried) were inconclusive (17). With troughs that have the convex side windward, it appeared that an aspect ratio of 10 (collector length/collector aperture) resulted in forces and moments close to those for an infinite aspect ratio. With the concave side windward, troughs with aspect ratios of 0 and 10 still exhibited lower drag than that expected for an infinite aspect ratio trough.
- Collector height mounting: The effects of mounting PV collectors and troughs at different heights (6,21,17) were studied. In both cases the forces increased monotonically with height, and the rate of increase is fairly close to that expected due to the change in the velocity profile with height, but varied somewhat for various angles of attack. The normal force on PV arrays and the parabolic troughs at zero angle of attack both conformed quite closely to the height velocity relationship. The most dramatic impact of height appeared to be with the pitching moments on parabolic troughs. The data in Ref. 6 shows that the pitching moment (not moment coefficient) can change by more than a factor of four (decreasing in absolute value) as the height, above the ground varies from 0.75 to 1.25 aperture widths.[11] With further increases in height, the pitching moment appears to increase (absolute value) monotonically. This drastic variation in moment is probably caused by ground effects (e.g., blockage and increased turbulence), since in an ideal condition one would expect the moment to increase monotonically with height according to the boundary layer variation. This is consistent with other data in Ref. 6, where the maximum pitching moment measured in the boundary layer tunnel is three times larger than the corresponding moment in a smooth flow tunnel test. This last piece of data indicates the significant impact of the combined ground and boundary layer effects.

Clearly, the issue of load reduction is not totally resolved. Many of the test results are either only qualitative or at least very difficult to extend to collectors of any arbitrary configuration and placement. However, the results of the various tests are remarkably consistent and indicate that a very strong effort should be made to take advantage of both field and fence effects in the design of solar collector systems.

Planned Testing

There is a limited amount of testing being planned for the near future. With heliostats, field instrumentation for the Barstow facility is being investigated and planned for future field testing. At this point in time, wind velocity measurements at several points within the field are planned, and several heliostats will be instrumented with multiple load cells mounted under the mirror modules. This should result in a good indication of total loads as well as gross pressure distribution variations.

Parabolic troughs have been instrumented in the field at Willard, N.M. to measure lateral and lift wind loading. Some of the inherent difficulties with field testing were encountered when only seven hours of applicable data were collected over a four month period due to the vagaries of the wind. The data has not yet been analysed. On-site pressure distribution tests on troughs are now being planned

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[10] Typical average ground cover ratios (GCR) being used for solar thermal systems are 22% for heliostats and 33% for both dishes and troughs.

[11] As the collector is pitched so that the bottom edge comes closer to the ground, the stagnation point can move down, tending to increase the moment if the flow is restricted (or blocked) by the ground.

for the Coolidge experiment in Arizona. Wind tunnel tests are also being planned to compare with the field tests.

The Boeing Co., under contract to the Jet Propulsion Laboratory, is currently (28) completing pressure distribution tests on photovoltaic arrays to confirm previous theoretical work (27) in support of their structural optimization efforts. Similarly, Sandia is planning pressure distribution tests to support their efforts.

Dynamics

Dynamic properties of both the wind field and the collector structure can affect the performance of solar collectors. Short term dynamic effects of the wind stream are considered in wind tunnel tests, as mentioned earlier, to the extent that turbulence intensity and scale are modeled correctly. However, the complexities associated with the dynamic interaction of the collectors and the wind have received little attention to date[12], primarily because of the current limited understanding of the mean loading problem. What little data (on heliostats) there is, infers that flutter does not appear to be a major concern (7). Further, wake galloping in fields of collectors may have some impact on collector design (25), but more study is needed to define the magnitude of the problems corresponding to these and other dynamic effects.

DISCUSSION AND CONCLUSIONS

Wind loading investigations to date have focused on establishing safe limits for steady state loading of rigid structures and verifying the initial design approaches for the various solar concepts. As such, the effort has been successful, and has contributed greatly to the recognition and qualitative understanding of many of the physical phenomena involved. Further, the effort has resulted in a sound understanding of the mean loading on individual solar collectors in steady state flow conditions. This knowledge base requires further extension to take advantage of potential large load reduction benefits and to establish well understood loading specifications for current and low cost collector systems which in turn will permit the development of collectors with optimal performance/cost ratios.

There are a number of possible load reduction techniques which could be pursued; the most significant of which is the benefit provided by fences as well as that provided by shielding with appropriately designed fields. Although no collector designs currently take full advantage of this apparent benefit, when taken in toto, these tests consistently show that load reductions of three or possibly more seem feasible for an appropriately designed field and fence system. A more detailed quantitative understanding of the wind interactions phenomena operative within the field is however needed to take advantage of this potential.

Consistent with developing the required understanding, there are two areas where further wind loading investigations should be pursued.[13] The first is the accelerated generation of appropriate field data, along with its subsequent correlation with existing theoretical and wind tunnel data. This will not only lead to a better understanding of the applicability of current wind loading predictive and design methods to real situations, but will add significantly to the overall credibility of collector system structural integrity. The second area is the continued effort to develop an understanding of the physical phenomena operative within a collector field for the purpose of developing more quantitative bounds for load reductions. More specifically, the wind tunnel can be used as a tool to develop correlations of turbulence intensity and scale, as well as velocity profile decay as a function of field and barrier parameters (i.e., such as fence height and porosity, collector packing density, distance into the field etc.).

A third area of somewhat less urgency, but which must be eventually thoroughly evaluated is the dynamic interaction of the collector with the wind stream. Specific problems include the understanding and mitigation of potential fatigue and resonant failures associated with this dynamic interaction.

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[12] An explanation of the various dynamic phenomena of concern is given in (1); along with a description of inherent difficulties confronted when modeling these phonomena.

[13] More detailed recommendations can be found in Ref. 1.

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