DEVELOPMENT OF A HIGH EFFICIENCY CEILING FAN

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Introduction

The potential of ceiling fans to improve comfort during the cooling season is well documented (Rohles et al., 1983; Fairey et al., 1986). There are at least two cases: In the first where air conditioning is unavailable, adding ceiling fans may significantly improve building comfort and health although actually increasing energy use. However, the more common circumstance is where ceiling fans are used with the objective of providing a higher cooling system thermostat set point with acceptable comfort. Fans can also potentially avoid the use of air conditioning during "swing" seasons. Although studies commonly suggest a 2-6°F increase in the thermostat set point, data from 386 surveyed Central Florida households suggests that although fans are used an average of 13.4 hours per day, no statistically valid difference can be observed in thermostat settings between households using fans and those without them (James et al., 1996). Part of this may be due to the lack of sufficiently wide air distribution coverage within rooms (Rohles et al, 1983; Sonne and Parker, 1998).

Studies touting potential cooling savings of up to 40% have usually been sponsored by fan manufacturers (eg. A.D. Little, 1981). These often make unrealistic assumptions such as presuming that occupants are within four feet of a fan with only one fan in use and a 6°F elevation of the thermostat setting. An environmental chamber study by *Consumer Reports* showed that the long-reported de-stratification benefits when heating are largely unsubstantiated (Consumer Reports, 1993). Thus, benefits from ceiling fans are only to reduce cooling needs and this is completely contingent on sufficient changes in interior comfort to warrant raising of the cooling thermostat.

Two other factors must be taken into account in assessing the benefits of fans: their actual energy use and the added internal heat gains produced by the fans during operation. The measured electrical demand of ceiling fans varies between 5 and 115 Watts depending on model and speed selection. A power demand of 40 W at medium speed is probably typical (Chandra, 1985). Thus, a fan used for six months of the year would use 175 kWh. With 4.3 ceiling fans in an average Florida home, this amounts to about 800 kWh of fan energy consumption --about 5% of total electricity use. Also, all of the energy use of fans is eventually converted to heat within the home which must eventually be removed by ventilation air or the cooling system.

DESIGN OBJECTIVES

In the fall of 1996, the Florida Solar Energy Center (FSEC) set out to create an improved ceiling fan design which would provide better air moving efficiency while reducing energy consumption. The design objectives were as follows:

1) Maximum air flow (cfm) per input watt (typical designs produce 150-200 cfm/W)
2) Air flow distribution (uniform air movement throughout the room)
3) Quietness of operation

In lieu of a more efficient motor, the goal was to see if a smaller, less expensive motor could be used with superior fan propeller blades to create performance equivalent to the best ceiling fans using larger motors, providing both improved energy efficiency, potentially lower cost, and superior comfort.

DEVELOPMENT

FSEC worked with *AeroVironment* of Monrovia, California to come up with a ceiling fan propeller design which would improve energy efficiency and comfort. Numerical simulations suggesting three potential ceiling fan designs.

The design objective was a fan producing air flows of 2 meters/second across the blade radius at a speed of 150 - 200 rpm. We evaluated the three designs and selected the tapered blade design which suggested the best performance. The development team made refinements in the design in March of 1997, providing cross sections for design Ceiling Fan-1 (CF-1) which was later renamed the *Gossamer Wind*. The design featured tapered, twisted blades with a true air foil. The simulated cross sections are shown in Figure 1.

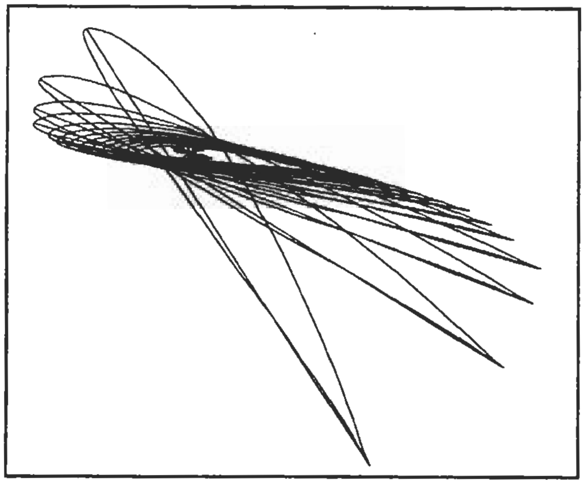

Figure 1. Computer generated air foil sections showing how fan blade twist increases as ceiling fan root is approached.

The numerical simulations, estimated that the prototype fan would provide roughly twice the air moving efficiency that would be obtained with conventional flat untwisted blades. It was estimated that about 8 watts of shaft power would be required to meet rated performance.

Two approaches were made to produce the blades. One method, to create a wood mold on which fiberglass shells would be cast was attempted, but failed. We eventually decided to create each prototype blade by using a cross section of the blade airfoil at each of the measurement stations mounted onto a metal crossbar running the length of the blade. Struts were then glued between the ribs to provide racking strength with thin balsa wood sheets applied to the ribs as a cover. These were then glued in place and sanded smooth. Four blades were eventually produced with very close tolerance to the original design.

The blades were then mounted on adjustable brackets so that the pitch of the blades could be altered during test. The balsa blades are approximately 6.5" wide at the blade root tapering to just 2.5" at the rounded tip. The blades are approximately 20.5" long with an estimated surface area of 93 square inches. Unlike the flat bladed ceiling fans, the propellers for the design are highly twisted. Under the design specification, the pitch with respect to the plane of rotation varies from 26.5 degrees at the blade root to 6.9 degrees at the rounded blade tip. The airfoil shape is based on a low velocity design (GM15) derived from wind tunnel testing performed at the University of Illinois. Each prototype blade weighed 175 grams with mounting hardware. The overall blade diameter with mounting hardware was 52 inches – identical to a standard ceiling fan size. The final design is shown in Figure 2.

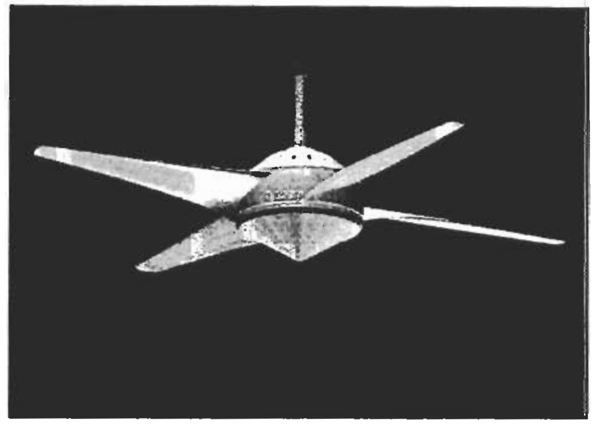

Figure 2. Computerized rendering of the prototype ceiling fan. Blades are true air foils with both taper and twist.

TEST BENCH

In May of 1997 a test laboratory was set up at FSEC. The test bench consisted of three major elements. First was a digital hot wire anemometer which was mounted on a tripod at a 56 inch height with an accuracy of 0.05% of full scale reading. The second was a precision digital watt hour meter with a resolution of 0.1 W. A hand-held infrared tachometer was used to measure ceiling fan speed (rpm).

During the early summer 1997, three conventional ceiling fans were acquired for comparative testing. These included two *Emerson* models and one *Hunter* ceiling fan. The *Hunter* fan (*"Summer Breeze"*) was recently rated as one of the best ceiling fans in terms of air moving efficiency in a recent issue of Consumer Reports.[1] The two *Emerson* fans consisted of a low cost model (*"Northwind" CF705*) and a more expensive 5-bladed fan (*"Premium" CF4852*) which represented a part of the upper end market designed to move more air (larger K55 motor). The low cost fan, with a cost of $70, represented a very large part of the current ceiling fan market. It consisted of a fan with four flat blades and an inexpensive 50 watt shaded pole induction motor. The flat blades had a nominal tilt of 12.5 degrees although we measured only an 8 degree pitch on our test bench when assembled. The flat ceiling fan blades were identical for both ceiling fans and represented the standard design within the industry. They consisted of rounded rectangular blades with a width

[1] "Stirring up a Breeze: Ceiling Fans Test," Consumer Reports, Vol. 62, No. 7, July, 1997, p. 44-47.

of 5" at the blade root up to 5.5" at the tip and were 20 inches long. The estimated blade area was approximately 103 square inches. They were made of painted wood and each had a measured weight of 329 grams with mounting hardware.

The fans were mounted using existing hardware as they came out of the box. Each tested fan came with only a 3" down rod which connected the fan motor to the mounting bracket. This resulted in the fans being installed so that the ceiling to blade tip distance was about 9.25". The air flow measurements were made underneath at a distance of 43" from the floor in accordance with ASHRAE Standard 55-1992.

Air flow measurement locations were established for the measurements by marking off 12 stations with the first immediately below the centerline of the fan and the others at six inch increments from the centerline (Figure 3). Since the fan blade and motor has a diameter of approximately 52", the first six stations comprised the locations which cover the blade sweep; the remaining six stations (3 - 6 ft from the fan centerline) represented the fan air entrainment zone.

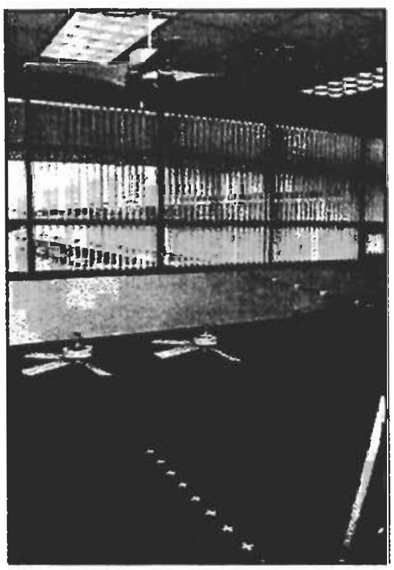

Figure 3. Air velocity test evaluates air moving efficiency at ½ ft. increments from fan center.

TESTING

Testing was done by mounting each fan in turn and evaluating the three fundamental quantities:

- Flow (m/s)
- Power (W)
- Speed (rpm)

The air flow measurements were taken at each of the air flow stations. Three repetitions were conducted for each air flow station. The fans were first tested with the existing down rods which had been provided. This resulted in the fan blades being about 10" from the ceiling above. The results are shown in the tabular data as well as in the figures below.

Figure 4 shows the measured air flow in meters/second for the four differing fans at low speed operation over the six foot region comprising the measurement area. The legend also provides performance data in terms of motor power consumption and fan rpm. The prototype fan shows clearly superior performance to the flat bladed fans. The Hunter fan provides the most competitive comparable performance. Note that the *Emerson CF705* fan and the prototype fan are using the same motor with different blades. Thus, it is possible to see the impact of the improved blades alone by comparing these two performance curves.

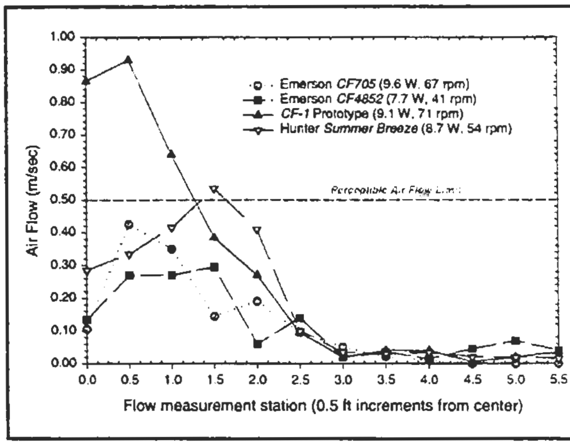

Figure 4. Air flow performance of fans at low speed.
(Prototype fan: 5° pitch @ 24, 9.75" below ceiling)

Figure 5 shows the measured performance of the four fans at high speed. Note that the power draws of the fans are quite different except for those of the prototype and the *Emerson CF705* which use exactly the same motor. Only the *Emerson CF4852* fan is able to match the air flow performance of the prototype fan and this comes only at considerable energy cost. The *CF4852* with its larger K55 electric motor uses 93 Watts as opposed to the 50 watts used by the prototype – a reduction in relative energy use of 46% with similar air flow. The *Hunter* fan has the next best performance since its motors draws only 75 Watts at high flow. Interestingly, the data show that all the 52 inch fans only provided good air flow (>0.50 m/s) over the radius of the fan blades (2 feet – shown at measurement location five). All increases to measured air flow are essentially negligible by the time measurement station seven is reached (3 feet out from the fan). This argues for larger fan blades to increase fan coverage – a fact acknowledged in a

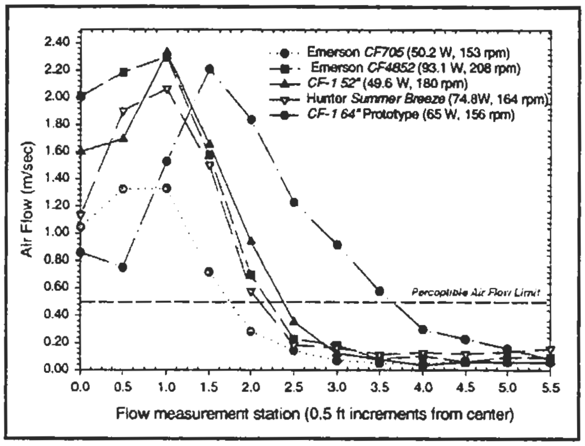

Figure 5. Air flow performance of fans at high speed.
(Prototype fan: 5° pitch @ 24", 9.75 below ceiling)

previous study (Rohles et.al., 1983) assessing ceiling fan impact on comfort.[2]

COMPARATIVE PERFORMANCE

The measured air velocities (m/s) between each measurement station was multiplied by the area of that specific area (m^2) to yield a volumetric flow (m^3/s). The flows for each fan were then summed over the relative areas between air flow stations extending out to three feet from the fan center where the flows of all fans dropped to background values (>0.1 m/s). The total flows were then converted into cfm for each fan. An efficiency index was produced by dividing the total cfm per fan by the measured motor wattage (cfm/W). Table 1 provides the results for the low fan speed; Table 2 shows the same for the high speed setting.

Table 1
Comparative Fan Performance and Efficiency at Low Speed

Value	Emerson CF705	Emerson CF 4852	Hunter Summer Breeze	Prototype CF-1 52"	Prototype CF-1 64"
CFM	1087	1001	1865	1907	1870
Watts	9.6	7.7	8.7	9.1	10.8
CFM/W	113	130	214	210	173.2

Table 2
Comparative Fan Performance and Efficiency at High Speed

Value	Emerson CF705	Emerson CF 4852	Hunter Summer Breeze	Prototype CF-1 52"	Prototype CF-1 64"
CFM	3110	6057	5339	6471	9807
Watts	50.2	93.1	74.8	49.6	65.0
CFM/Watt	61.9	65.1	71.4	130.5	150.9

The CF705 and CF-1 fans use the identical motor, so the improvement in performance is solely a reflection of the change in the efficiency of the propeller blades. The air moving efficiency of the *Emerson* motor is increased by 86% – nearly doubling the overall performance. Both the *Emerson CF 4852* and *Hunter Summer Breeze* use different motors, although power demand is similar. The low speed performance of the *Hunter* fan is similar to the CF-1 prototype, mainly due to the fact that its air flow is highest towards the edge of the ceiling fan blade tips which encompasses a larger area.

At high speed the disparity between the prototype fan and that of the other conventional models is even more pronounced. Keeping in mind that the only difference between CF-1 and the *Emerson CF 705* model is the improved blades (they use the same motor), the prototype shows a 111% increase in air moving efficiency. Not only does the CF-1 model have the greatest air moving efficiency, but it also has the greatest absolute flow – even more than the *Emerson* model using a motor which draws 88% more power. Finally, note the superior air flows produced by the larger 64" prototype, particularly at high speed.

[2] "...There are several important assumptions in this generality [that ceiling fans will save energy]." The 6°F temperature difference is based on the results at [test locations] V_3 (0.46 m/s) and V_4 (1.0 m/s)....A fan generates air velocities of these magnitudes only over a relatively small area near the fan. This level of energy savings is possible only if sufficient fans are available to generated velocities comparable to V_4 at locations commonly occupied by people."

AUTOMATED CEILING FAN CONTROLS

Conventional fans use pull chains or rotary wall switches which are often unintentionally left on even when no one is home. For instance, a survey of home owners by the Florida Power and Light Company, found that the average ceiling fan is on 13.4 hours per day with nearly a third of fans left on constantly year round (James et al., 1996; Sonne and Parker, 1998).[3] This wastes electricity, since a ceiling fan can only improve comfort if someone is there to feel its air motion.

Smart controls for the fan were designed to increase its convenience, energy savings and comfort potential. A 360-degree infrared motion sensor control automatically activates the fan when anyone enters a room and switches off when occupants are gone. Another control circuit, under development, adjusts the speed of the ceiling fan in response to room temperature conditions. A switchable photo optical sensor will be used in the production unit so that the fan will not be turned off by a lack of motion in darkness. This will prevent the control from turning off the fan in bedrooms while occupants are sleeping.

The automatic control system for the fan has been developed in conjunction with the *Wattstopper Corporation*. Photographs of the prototype controller based CI-200 unit, is illustrated in Figure 6.

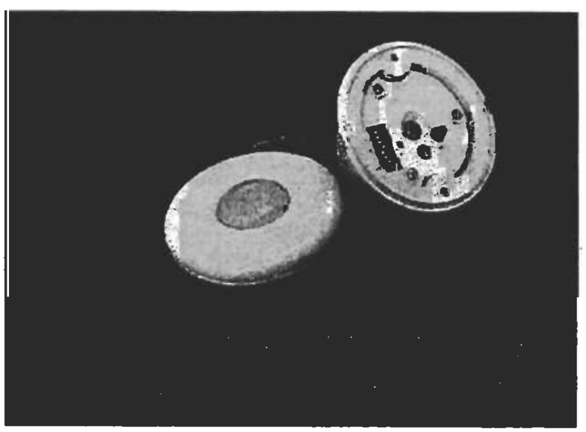

Figure 6. Control unit showing internal switch settings (sensitivity, light and time delay).

Control Logic

Operation of the control mechanism for the ceiling fan is described in the flow chart shown in Figure 7 (at the top of the next page). The control system sequence begins to operate when electrical power is applied to the device. Once activated, the passive infrared (PIR) sensing mechanism scans through a 360 degree compound Fresnel lens. If it senses movement within its field of view, it checks if manual override has been set or the control does not sense the activation thermal limit. If the PIR sensors doesn't detect movement, it checks to see if the set time delay is expired. If the time delay has expired, it switches off the fan motor.

If the time delay has not expired, it checks to see if manual override has been set or the control unit does not include temperature based speed control. If the override is specified or the unit is an occupancy sensing only model, it maintains the current ceiling fan speed at state.

If manual override is not set (or the control unit does not include temperature based speed control), the control checks to see if the room temperature is below the minimum setting. If it is, it deactivates the fan motor. Otherwise, it the control checks to see if the temperature is greater than the low setting and less than the mid-point between the high and low setting at state. If this is true it sets the fan speed to low speed. If the temperature is equal to or greater than the mid point of the set range, the control determined whether the temperature is less than the high temperature setting. If it is not, it sets the fan speed to medium. If the temperature is greater than the high speed value, the fan is set to high speed at state. The entire sequence of readings and actions are then repeated as long as the fan control is powered.

Energy Efficient Light Kit

Conventional fan light kits use a 100 W linear halogen lamp or three or more 40 W incandescent bulbs. These, which are often hard to reach, use considerable electricity when operating and require frequent replacement. The prototype has an energy-efficient light kit which fits within an attractive housing and provide up to 12,000 hours of superior lighting without a lamp change. Further, its energy savings will typically amount to more than $100 over the life of the fan.

Most modern ceiling fans use a J-type halogen 100 W light kit (R7S halogen lamp: 1400 lumens, 2900K color temperature). The lamp's power consumption more than doubles the fan energy use when the lamp is energized: a ceiling fan motor typically only draws about 50 - 90 W at high power!

[3] A total of 384 homes were surveyed; there were 4.3 ceiling fans in an average Florida residence.

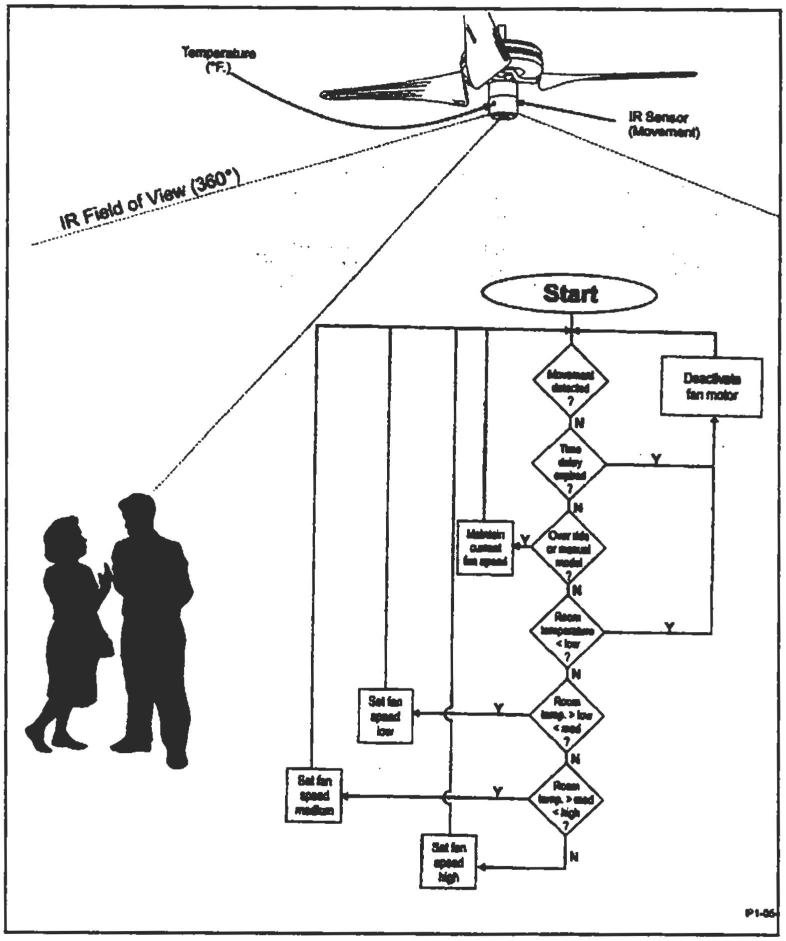

Figure 7. Automated control logic flow chart.

To address this problem, we adapted a 20 W circline lamp to fit within the standard lens of the light kit housing. The lamp puts out a pleasing warm light, which provides about the same lumens as the halogen (1450 lumens), although with a somewhat softer illumination. Unlike magnetic ballasted fluorescent lamps, the electric ballast in the *2620C* provides instant-on capability.

Even more important though is the life expectancy: the compact fluorescent lamp (CFL) has a MTBF of 12,000 hours versus 2,000 hours for the 100 W halogen lamp. Thus, the CFL lamp will likely not need changing over the life of the fan. If the lamp kit was used for 3 1/2 hours per day, the new light kit would save 1,022 kWh over a ten year period compared with the standard configuration – equal to a money savings for energy savings alone of $82 at typical electricity prices.

Further, six *R7S* lamps would have to be replaced over the same time period; a current representative price for these lamps is $5.75 each: a total added cost of $34.50, not to mention the aggravation of going out to buy and installing the replacement lamps.

The retail price of the CFL lamp we used is $15 – cost to manufacture in production would certainly be less. Thus, the new light kit alone in the prototype could save consumers at least $100 over the life of the fan. The more efficient fan will provide even greater savings as well as improved comfort.

Noise

Another question to be addressed was the noise levels of the different fan blade types. This was tested using a decibel meter. The background noise was measured first, then the fan motors as shown Table 3.

Clearly, the improved design is the most quiet. The differences are larger than they appear since the decibel scale is logarithmic – sounds 10 dB louder have 100 times more sound pressure. It is expected that the quieter blade design will be more aesthetically appealing to consumers.

Table 3
Sound Pressure (decibel) Levels at High Speed

Background Noise Level		CF-1 Prototype	Hunter "Summer Breeze"	Hampton Bay "Landmark"
Test #1	57 db	57 db	62 db	60 db
Test #2	57 db	57 db	62 db	60 db
Test #3	57 db	58 db	64 db	61 db
Average	57 db	57.3 db	62.8 db	60.3 db
Decibels over background		+0.3 db	+5.8 db	+3.3 db

Advantages of the CF-1 Prototype in Application

- Fan blades can be made part of the standard equipment with a smaller less expensive motor and still provide superior air flow to that achieved with larger more expensive motor and flat blades.
- Controls provide savings by reducing fan on-time when rooms are unoccupied, along with improved convenience.
- The resulting combination of an existing motor with the improved blades is greater energy-efficiency. This saves ~$10 - $20 per year in operation. First cost of the improved ceiling fan may be reduced by $50 over a fan providing similar performance using the K55 motor with flat blades.
- Energy efficient light kit can reduce associated energy use by 80% saving approximately $10 per year and reducing frequency with which bulbs must be changed.
- Improved aerodynamics of tapered blades are more quiet in operation than flat blades.
- If mated with a larger fan motor, a larger version of the current fan blades (e.g. 64" or 72" rather than 52" diameter) can potentially provide superior air flow to any ceiling fans with flat untwisted blades.

FAN MOTORS

The shaded pole motors used by conventional ceiling fans are very inefficient. This is both due to limitations in the impedance protected shaded pole design as well as the low rpm rates at which ceiling fans operate.[4] Tests on a small dynamometer of a conventional ceiling fan motor at Oregon State University showed a useful motor shaft output of only 12.8% at high speed (64.9 W) and only 2.6% at low speed (11.1 Watts).

All of the motor inefficiency is converted to heat. Heat produced by ceiling fan motors increases air conditioning cooling loads. The infrared thermograph in Figure 8 shows shading proportional to temperature. Waste heat produced by the motor as well as the very low efficiencies achieved, underscores the need for smaller, more efficient motors.

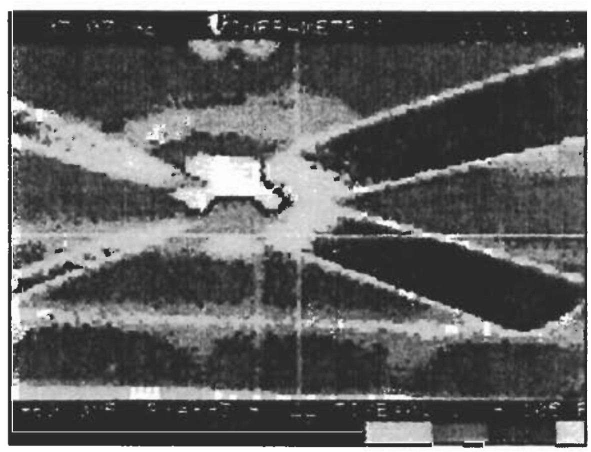

Figure 8. Infrared thermograph of ceiling fan showing heat produced by the motor.

FUTURE WORK

Currently, a light-weight and highly durable prototype blade is being tested that consists of a foam core material. Once this is fully developed, it will be tested to determine which size motor is best for both the 52" and 64" new prototypes. This will directly

[4] Electric motors operate most efficiently in rpm ranges of 3,000 - 6,000 rpm rather than the 30 - 200 rpm required for ceiling fans. Unfortunately, gear motors or similar ideas do not work well due to friction losses and noise.

lead to a pre-production prototype version which will precede large-scale manufacturing.

Since it has been determined that the new blade design is superior to standard flat blades, a larger version is also being constructed to provide better room airflow distribution. The larger design has a 64" diameter and was constructed of plastic using stereo lithography.

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