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INCREASING FIXTURE EFFICIENCY FOR COMPACT FLUORESCENT DOWNLIGHTS

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Compact fluorescent fixtures can produce a thermal environment that reduces light output by as much as 20%. Thermal management by venting can limit this loss.

RECESSED downlights are one of the most popular fixtures used for lighting commercial buildings. The vast majority of these fixture use incandescent lamps* in sizes ranging from 50 to 150W. Because cost and energy efficiency are a growing concern in the lighting design process, fixtures using compact fluorescent lamps* (CFLs) have made significant inroads into the incandescent market. While providing high efficiency, these fixtures also reduce operating cost. CFLs have an efficacy* about four times that of incandescent lamps; they also last about 10 times longer, thus providing maintenance savings.

Light loss and efficiency

A major problem in applying CFL fixtures is the relatively low efficiency of the fixtures themselves. Fixture efficiency is defined as the ratio of the total light output from a fixture to the total light output from a lamp/ballast system, evaluated under standard conditions. The efficiency for many CFL recessed downlight fixtures is between 50 and 60%. In other words, nearly half of the light produced by the lamp is lost. Approximately half of *this* loss can be attributed to thermal loss, with the other half due to optical loss (loss due to the reflective geometric characteristics of the fixture).

Thermal loss occurs because most light fixtures have a highly constricted geometric environment for the temperature-sensitive CFLs. The reflector geometry of most recessed downlights tends to produce a *convective trap*, which results in a stratified layer of warm air surrounding the CFL. This layer of air *reduces* the convective and conductive cooling of the lamp, causing elevated lamp temperatures.

Reduced lumen output of CFLs will effect the energy conservation potential of these lamps as replacements for incandescent sources. In nearly all major demand side management (DSM)* programs, "lumen-matching" is one of the most important criteria in incandescent replacement. Therefore, increasing lumen output and efficiency of CFL downlights is an important design consideration in the development of CFL fixtures.

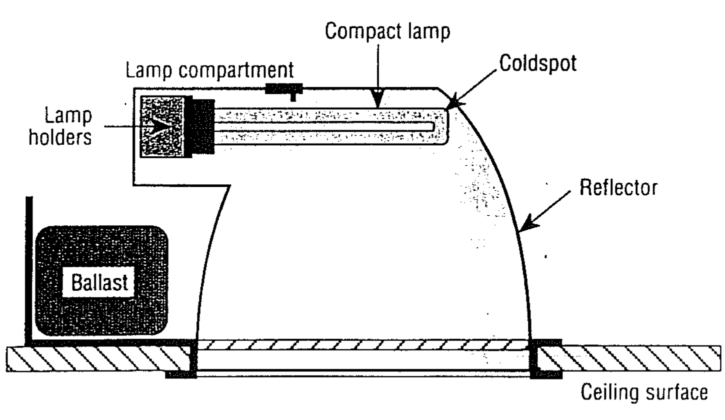

Fig. 1. Cross section of a standard fixture with no venting geometry.

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CFL operation

Inside a typical fluorescent lamp, mercury atoms emit ultraviolet (UV) photons that strike the phosphor coating on the inside surface of the lamp. This coating, in turn, emits light within the visible part of the electromagnetic spectrum.

The loss in light output from CFLs operating in warm ambient environments is due to the elevated mercury vapor pressure inside the lamp, which in turn, is caused by higher than normal lamp wall temperature.

Internal mercury vapor pressure is a direct indication of the number of mercury molecules in the vapor phase. Only the mercury in vapor phase can be involved in the radiation and light emitting process. However, there is an optimum number of mercury molecules for best results and thus, an optimum mercury vapor pressure. When, due to elevated temperatures, this pressure *exceeds* optimum level, the additional vaporized mercury molecules *interfere* with the UV radiation and light emitting process, i.e., a UV photon is absorbed by adjacent mercury molecules instead of by the phosphor coating. Hence, when the lamp wall temperature gets too hot, light output and efficacy drops.

Lamps typically produce optimum light output and efficacy in ambient environments of approximately 25°C.

*Definition of words followed by an asterisk (*) will be found in "TERMS TO KNOW" on page 60.

TERMS TO KNOW

Compact fluorescent lamp (CFL). A self-supporting, single-ended fluorescent lamp of small, compact shape with a single base that performs the entire mechanical support function.

Demand side management (DSM). A voluntary program in which users of electric power take actions to reduce the electrical demand level of their facility. A DSM program involves coordinated action by both the serving utility and the customer. Some utilities offer assistance to customers via incentives, such as rebates when more efficient equipment is purchased and/or engineering assistance is provided to make a customer's electric system more efficient and/or more effective by peak-load shifting.

Efficacy. Technically known as luminous efficacy of a source of light. The quotient of the total luminous flux emitted by the total lamp power input, and expressed as lumens per watt.

Fluorescent lamp. A low-pressure mercury electric discharge lamp in which a fluorescing coating (phosphor) on the inside of the lamp's glass tube, transforms some of the ultraviolet energy that is generated by the electrical discharge into visible light.

Incandescent lamp. A lamp where the light is produced from a filament that is heated to incandescence by an electric current.

Photometer. An instrument for measuring photometric qualities such as luminance, luminous intensity, luminous flux, or illuminance.

Plenum. There are various definitions, the one applicable to this article being the space between the top of a finished or suspended ceiling and the underside of the floor or the roof above. This space is referred to as a ceiling cavity plenum. This space may be used to supply air into or return and/or exhaust air from occupied areas, providing that all materials exposed to the airflow shall have specific combustible limits. A ceiling cavity plenum is frequently used for carrying wiring and other utilities, and often has lighting fixtures protruding up into it. Although defined as a plenum, the rules for wiring are covered in Sec. 300-22(c) of the NEC under the heading, "Other Space Used for Environmental Air".

The *cold spot* in a lamp is where all the mercury *not* in vapor phase condenses in a liquid form. Typically, in a bent tube CFL, the cold spot is at the end of the lamp furthest away from the filaments. Since the total amount of mercury inside the lamp at any give time is fixed, the amount of mercury condensed at the cold spot controls the vapor pressure. That amount of condensed mercury is determined by the lamp wall temperature at that spot. The minimum lamp wall temperature (MLWT) is at that location and is directly affected by the thermal environment surrounding the lamp. In tightly closed or sealed fixtures, the lamp temperature can be very hot, resulting in reduced light output and efficacy.

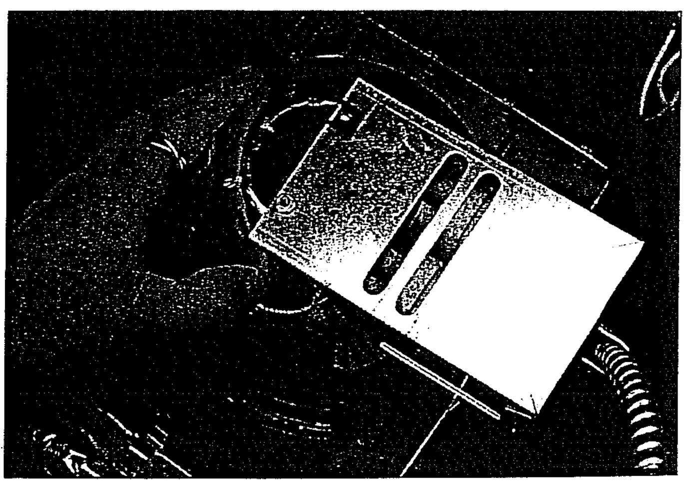
Convective venting using passive ventilation is presently being researched as an emerging technique for limiting thermal losses in recessed downlights. This technique involves the use of strategically located apertures in the recessed downlight fixture to promote passive ventilation through the lamp compartment into the plenum*, thus removing heat from the lamp compartment. This procedure allows the lamp to operate in a significantly cooler environment.

Working with geometries of experimental fixtures

A number of experiments were conducted with fixtures having two 26W, quad-tube CFLs in a horizontal configuration. These particular fixtures had spun aluminum reflectors, horizontal lamp compartments and lamp holders, and two side-mounted core-coil ballasts: One of the more common compact fluorescent geometries.

For each experiment, fixtures were modified to incorporate a particular venting geometry, as noted below.

Standard fixture, no venting. Fig. 1 (see page 59) is a cross section of the fixture, illustrating the major components and horizontal position of the lamps. This fixture, without any type of thermal management system, serves as the comparison or industry standard. Most conventional fixtures have such a fairly



View of the top of a typical compact fluorescent fixture showing the horizontal mounting of two 26W CFLs.

View looking up into the fixture showing the lamps and the reflector geometry.

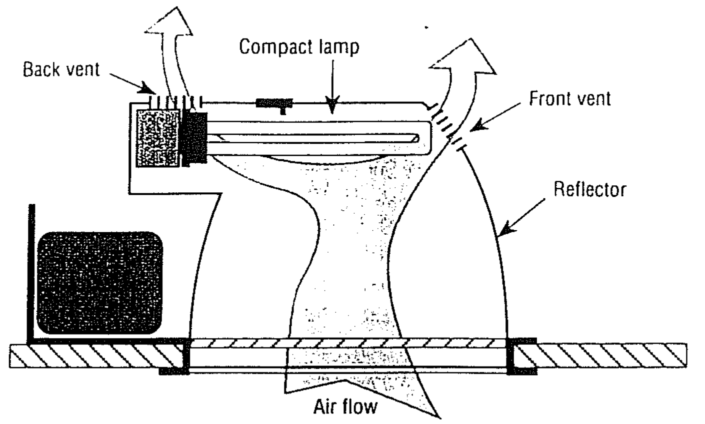


Fig. 2. Cross section of a fixture with front and back venting geometry, illustrating the air flow through the fixture.

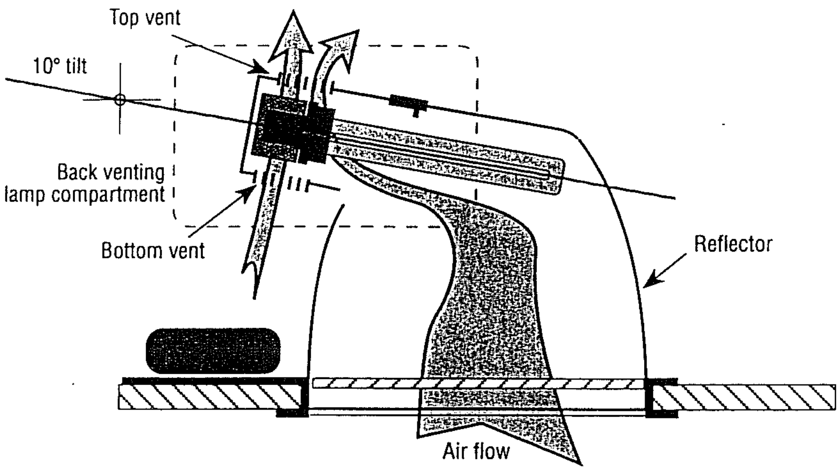


Fig. 3. Design with two ventilation paths for enhanced back venting with tilted lamp compartment.

constricted lamp compartment, resulting in *elevated* lamp-wall temperatures due to the stratified air mass surrounding the lamps.

A number of fixtures are measured in a simulated plenum, showing that thermally-based losses in light output range between 15% and 25%, depending upon the number of lamps and how the lamps are ballasted. For a typical double, 26W recessed downlight, losses are approximately 20%.

Front- and back-venting configuration. This configuration, as represented in the cross section shown in **Fig. 2**, uses venting apertures to promote passive ventilation through the fixture. The fixture utilizes front apertures located directly in front of the lamps to cool their cold spot region. Back-venting apertures located at the back of the lamp compartment remove heat from the filament and socket region.

The experimental simulations with this fixture configuration show that most of the thermally-based losses in light output can be lessened with cooler lamp temperatures. Passive ventilation through the lamp compartment is very effective in eliminating the stratified air layer within the reflector, thus allowing the lamps to operate near optimum light output.

This convective venting configuration represents an effective geometry for increasing lumen output in a constrictive lamp compartment. However, a primary concern is the optical losses due to *openings* in the reflector. The use of front venting geometry near the front tip of the lamps can produce as much as a 10% *optical* loss. This optical loss through the reflector ends up as light "leaking" into the plenum space above the ceiling.

Enhanced back venting, tilted lamp compartment. The third fixture geometry, as shown in **Fig. 3**, involves a new concept in fixture modification where the lamp compartment is tilted by 10° from the horizontal so that the lamps are sloped downward, with their cold spots being at the lowest point. This tilting lowers the tips of the lamps into a cooler region of the reflector, allowing gravity to act on the condensed mercury and permitting the formation of more stable cold spots away from the hot filaments.

The new design combines the basic concepts involved in thermal management and convective cooling. There is *no* front ventilation opening. Instead, the enhanced back venting has additional vents at the bottom of the lamp compartment. By making the vented area the highest part of the compartment, the resulting tilting and the sloped surface at the top of the reflector also promote a smoother convective flow of hot air, enhancing passive ventilation. Back venting in the rear of the lamp compartment over the socket region eliminates the problem of optical losses, as this rear portion is an optically inefficient area for both the lamp and reflector.

The experimental studies for this fixture show that most of the thermally-based losses in light output are eliminated. The lamps operate at or near optimum performance because of the convention through the lamp compartment.

The experimental procedure used

To assess the potential of various convective venting geometries, a series of experiments are conducted inside a simulated ceiling cavity plenum similar to that found in common commercial buildings. These experiments are designed to assess or track the change of a CFL's light output over time relative to the lamp's maximum light output, the latter being determined at the beginning of the experiment for each vented and nonvented geometry. The reduction in light output for each experiment correlates with the thermal environment as represented by the constrictive air flow, or how well the convective venting geometry works. By comparing the relative thermal losses, effective convective venting geometries can be identified.

Fig. 4 (see page 62) shows the general experimental set-up used for all the fixture tests, illustrating the major components and the simulated plenum system. Fixtures, powered through a voltage stabilizer, are mounted in the simulated plenum/ceiling system. Temperatures are monitored with thermocouples attached to various fixture components, in both the lamp's internal compartment and the external plenum. Light output is monitored by a light sensor (photometer*) placed below the fixture and aligned with its center axis. Power and voltage readings are taken using an appropriate metering device. Data is collected on a computer-based data acquisition unit over a period of 10 hrs.

Lamps are initially seasoned for a period of at least 100 hrs to minimize errors due to lumen depreciation. Each fixture system is then operated for a 24-hr period prior to any experimentation for establishing a stable cold spot.

After this preliminary run, the fixture is allowed to cool completely before starting the experiment.

The experimental procedures employed in this investigation are directed only to measure the *thermal* performance of CFLs within certain fixture geometries. The light sensor placed directly under the fixture does *not* measure the total light output or the optical distribution of the fixture because it only sees a *small portion* of the fixture's total output.

Because thermal performance and light output of a fixture are *directly* related, changes in thermal operating conditions can be monitoring by changes in light output, which, as previously discussed, are due to changes in the mercury vapor pressure inside the lamp. This pressure is controlled by the temperature conditions surrounding the lamp (the temperature of the air that encompasses the lamp).

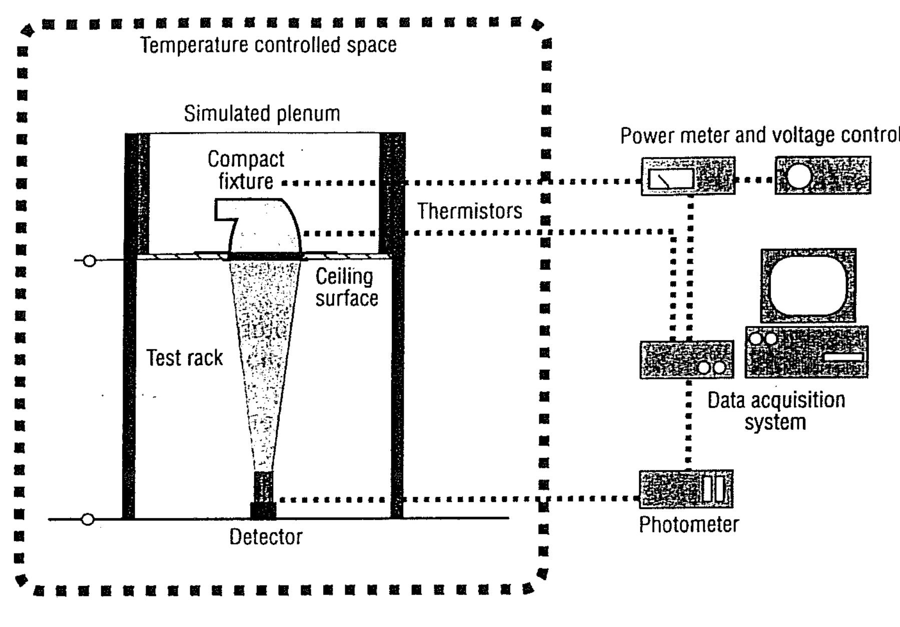


Fig. 4. The experimental set-up used for all of the fixtures tested. Also shown are the major components and the simulated plenum system. The signal from the light sensor (detector) goes to the photometer, which is connected to a data acquisition system.

Test results

All the data discussed in the following paragraphs refer to a CFL's *relative* light output, which is in direct correlation to the thermal conditions occurring within the fixture.

The main conclusion with the tilted fixture geometry is that significantly improved thermal performance can be obtained with back venting alone (without using front vents). This thermal performance is very similar to that of the fixture with dual front and back venting geometry. A significant advantage with the tilted/back venting geometry is that it eliminates the need for the front aperture, which, as previously discussed, results in a significant loss of useful light.

Thermography

To better understand the temperature variations involved in the thermal studies conducted on fluorescent lamps, thermal photography (infrared thermal imaging techniques) is used. An infrared imaging camera is used to take thermal pictures of the fixture within the simulated plenum. Infrared thermography produces two-dimensional heat transfer information in the form of a temperature contour map. Different colors correspond to various surface temperatures that can be determined from a calibrated color scale. Using thermographic imaging, the surface temperature of the fixture can be identified, and lamp cooling strategies, including convective venting, can be evaluated based on the thermal effects produced in the fixture.

Fig. 5 (see page 64) shows thermograms of the CFL recessed downlight fixtures produced by this thermal imaging technique. One fixture is a standard, unmodified fixture while the other has vents in the rear portion of its housing.

Temperatures at two identical points on each fixture are compared, and temperature differentials are identified using the color scale at the bottom of the figure. The thermogram illustrates that the temperature near the base of lamp in the vented fixture is 8°C *cooler* than the same point in the nonvented fixture. Also, the reflector surface temperature in the vented fixture is nearly 4°C *cooler* than in the nonvented fixture. The thermograms visually display what experimental data has already proven: convective venting is an effective thermal management technique for cooling the fixture and thereby increasing the light output and efficiency of the open recessed CFL downlight.

Dirt depreciation

One major concern of applying convective venting is the potential for increased dirt depreciation as room air is drawn into a fixture. Increased ventilation through a fixture introduces more particulate matter upon the reflector and lamp surfaces. This action possibly reduces the output of the fixture over time as more dust settles on these surfaces, negating potential benefits associated with convective venting.

To address this concern, an experimental approach was developed and appropriate apparatus was built to qualitatively assess the rate of dirt depreciation of *convectively-vented* CFL fixtures versus *standard nonvented* fixtures exposed to the same conditions. A simulated plenum was constructed within a dustproof chamber to monitor these fixtures as they operate in a dusty environment.

A reduction in light output is seen during the experiment, which runs for approximately 60 hrs with dust injections carried out during the time period. The *nonvented* fixture experiences a final reduction in light output of approximately 17%. The *vented* fixture has a similar but slower rate of dirt depreciation: approximately 14%.

The experimental data indicates that

the rate of dirt depreciation is slightly reduced with the use of convective venting. During these experiments, the convection patterns through the *vented* fixture can be easily observed as the air stream leaving the fixture contains particulate matter from the fixture compartment. Observed convection patterns within the *nonvented* fixture indicates a stratification of air within the lamp compartment, potentially leading to an increase in dust accumulation on lamps and internal reflecting surfaces.

Photos taken of the two lamp compartments readily show the pattern of dust deposit for the vented and nonvented compartments in the dirt depreciation study.

Conclusions

The above experimental data indicates that significant increases in light output and, therefore, fixture efficiency can be obtained with convective venting of the lamp compartment. The increases in lumen output are a direct result of the cooler lamp compartment and cooler lamp wall temperature. With the combination of enhanced back venting and tilted lamp compartment, a fixture can operate at 98 to 99% of the maximum light output.

As recessed downlights have widespread use in commercial applications, the significant increase in both lumen output and system efficiency of these fixtures, when they are used, will reduce energy demands for lighting. The additional lumens obtained from these fixtures will make fluorescent downlights even more attractive than their incandescent counterparts, both for renovation and new construction projects. Not only will this fixture design directly result in energy savings, but the increased light output means fewer fixtures will be needed to provide the required lighting level, thereby producing cost savings during both installation and maintenance.

Issues remaining to be addressed

Several issues, however, remain to be addressed with this new venting and tilting configuration. Among these is the offset target area of the downlight produced by the 5° to 10° tilt of the lamp compartment. Additional studies are needed to measure the changes in the optical distribution of the fixture incurred with this tilting. An optimum angle has yet to be identified that will maximize the benefits of this design while minimizing the optical distortion produced by the tilting. It is assumed that this angle will vary with fixture type, depending specifically on the fixture's geometry, thermal characteristics, optical design, and application. Also, as the convective flow is improved with a sloped upper housing, part of the fixture assembly will be redesigned to make the slope of the upper surface as smooth as possible. These issues are being addressed with the objective of providing a product that economically can be produced on a commercial basis.

Technology transfer

This research has been transferred to the lighting industry in a number of ways and has been cited in various industry publications, some of which are published by lamp manufacturers as design guidelines for fixture manufacturers. One result is that numerous manufacturers are giving increased consideration to the thermal implications in the design of CFL fixtures.

Various fixture manufacturers are, in fact, incorporating in their designs some of the conclusions reached by these investigations. Many horizontal-positioned CFL downlight fixtures presently on the market employ some variation of venting geometry to increase efficiency.

A number of manufacturers are considering a tilt configuration in the lamp compartments of new CFL fixture designs. ■

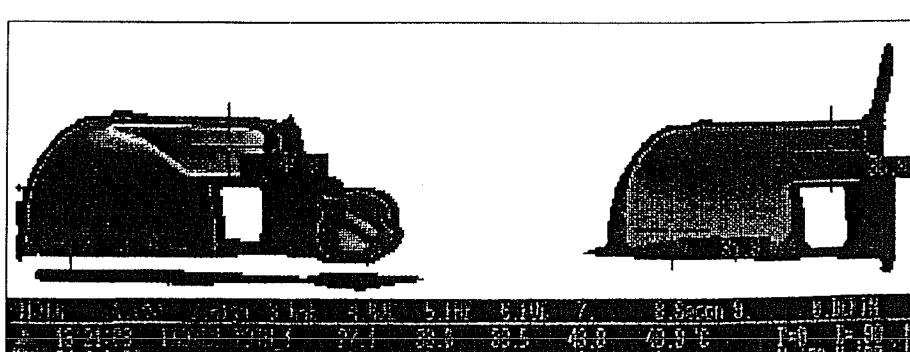


Fig. 5. These infrared thermograms (a thermal imaging technique) of the compact fluorescent recessed downlight fixture help provide an understanding of the temperature profile in a fixture.