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Abstract

This paper describes a new apparatus designed to model the physical parameters that affect fluorescent lamp performance under realistic operating conditions. These parameters include fixture type, mounting configuration, HVAC integration, and room air temperature, which directly determine the minimum lamp wall temperature (MLWT) and, therefore, the resulting light output of the lamp/ballast system. This apparatus is used principally to measure MLWT under operating conditions, which enables us to identify the effects the major parameters have on lamp/ballast system performance. Initial parametric results illustrate the use of this apparatus to provide representative MLWTs for a range of application conditions.

Introduction

Designers who wish to compare and select lighting systems and design lighting layouts that meet both illuminance and energy code requirements need accurate data documenting the combined performance capabilities of fluorescent lamp, ballast, and fixture systems operating under realistic application conditions.

Fixture type, ceiling construction, mounting configuration, HVAC integration, and room air temperature are factors that all affect the thermal environment of lamps to some degree. Because fluorescent lamps are temperature-sensitive, these factors may change the light output and power input properties of the system, in comparison to its performance as measured by routine photometric tests conducted under standard ANSI conditions. The inherent limitations in standard tests may introduce temperature-dependent errors in the lighting design calculation. These temperature-dependent errors arise primarily from variations in minimum lamp wall temperature (MLWT), which determines power consumption, light output, and efficacy of the lamp/ballast system. This functional dependence of light output on the MLWT of a CBM ballast and F-40 lamp is well documented [1]. Field measurements indicate that light output can be reduced by almost 25% as a result of the higher MLWT in luminaire applications compared to ANSI test conditions [2].

The luminaire/plenum/HVAC simulator was developed in order to understand how fixture design and ambient conditions affect MLWT and therefore the performance of the lamp/ballast systems. This simulator is used to selectively model realistic luminaire conditions in order to measure application-specific MLWTs. The MLWTs thus measured may then be used in conjunction with lamp/ballast performance data, expressed in terms of MLWT, to determine specific values of light output and efficacy for a given lamp/ballast/luminaire system.

This paper describes the function and operation of the luminaire/plenum/HVAC simulator and presents measurements made for a range of luminaire conditions.

Description of Experimental Apparatus

The simulator is designed for the measurement of MLWT for each luminaire tested. The minimum lamp wall temperature is a critical variable for characterizing the thermal performance of the lamp/ballast system because the cold spot temperature determines the mercury vapor pressure within the discharge, and therefore the input power and light output.

The interrelationships between the major components of the experimental apparatus are shown schematically in Fig. 1.

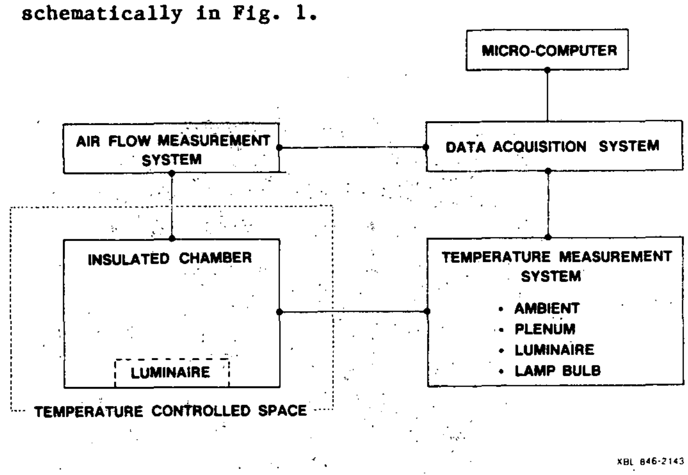


Fig. 1. Schematic of the major components of the luminaire/plenum/HVAC simulator.

Plenum Chamber: The plenum chamber consists of an insulated rectangular volume (5 ft x 5 ft x 3 ft). The chamber is instrumented internally with an array of thermistors for making both luminaire and plenum temperature measurements.

Figure 2a shows a cross section through the plenum chamber, indicating the appropriate scale and major components. A two-lamp troffer mounted with the ceiling plane is illustrated. Figure 2b is a photo of the plenum chamber.

Luminaire Mounting and Ceiling System: This system allows for mounting and instrumenting a variety of ceiling configurations, luminaire types, and support systems exterior to the plenum chamber, and installing (positioning and locking) the instrumented ceiling plane with the plenum chamber for testing. This system consists of a 5 ft x 5 ft horizontal ceiling support plane with an adjustable structure that accommodates any type of ceiling panel and luminaire type up to a 4 ft x 4 ft fixture.

Temperature-Controlled Space: The plenum chamber is situated in a room where the temperature can be controlled to ± 1/2^{o} C. The room air temperature can be varied between 60^{o} and 80^{o}F, encompassing the range of temperatures encountered in building environments. The tests reported on in this paper used a room air temperature of 25^{o}C ± 1/2^{o}C.

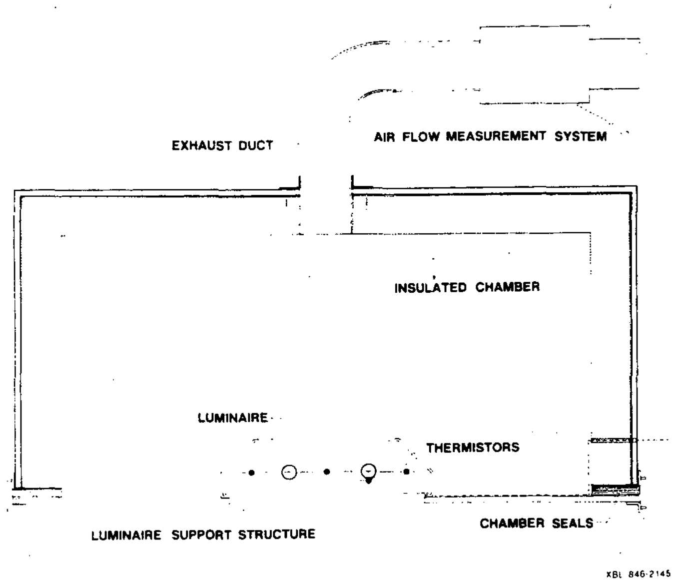


Fig. 2a. Cross section of plenum simulator and installed ceiling plane.

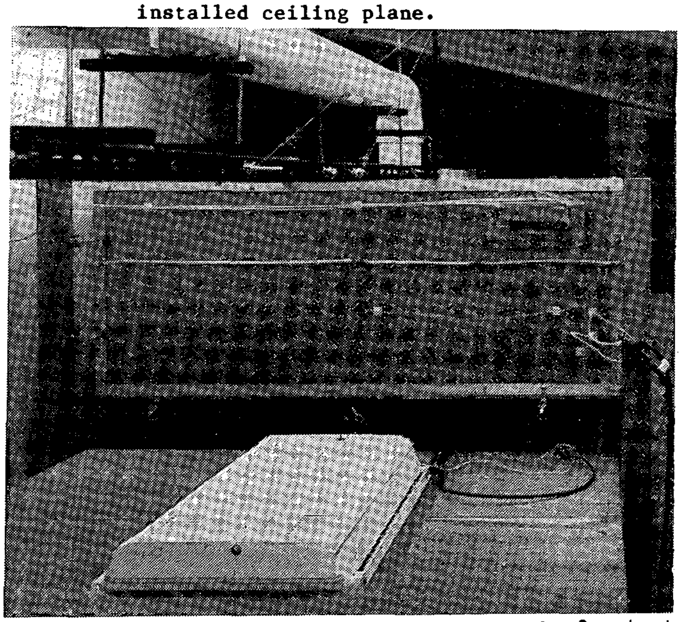


Fig. 2b. Photograph of plenum chamber. XBB 855-4074

Lamp Wall Temperature Measurement: A series of thermistors was attached to the underside of the lamp (20 cm on center) inside the luminaire. These thermistors were held in place using a spring-action plastic tie wrap in conjunction with a silicon-based thermal paste to ensure thermal contact. This method minimizes the potential disturbance of the thermal and light output characteristics of the lamp. The position of the MLWT changed under air flow conditions, along the axis of the lamps as a direct function of asymmetric flow characteristics within the lamp compartment. Thus, it is important to employ an array of thermistors along the length of the lamp, as a single point measurement may not accurately represent the MLWT.

Plenum and Fixture Temperature Measurement: The air temperature within the simulated plenum was measured with a three-dimensional array of thermistors suspended on monofilaments spanning the length and width of the chamber. The thermistors are accurate to $\pm 1^{o}C$.

Two thermistors in the exhaust ducting system measured the temperature of the return air leaving the plenum. This measurement was needed to determine the relative density of the return air for calculating volumetric flow rate given a differential pressure at the orifice plate. This temperature is also useful for understanding and sizing cooling capacities of an HVAC system operating under similar mechanical and luminaire conditions. The ambient air temperature in the lamp compartment was measured with an array of three thermistors. Ballast temperature was also measured throughout these tests.

Air-Handling Controls: The simulator was designed to model a range of return air configurations that are integrated with the operation of the luminaire. This includes combinations of both lamp compartment and plenum extract techniques, using a range of volumetric flow rates typically between 0 and 50 cubic feet per minute (cfm).

Employing an integrated return air function with a luminaire involves drawing room air through perimeter slots in the fixture into the luminaire and/or plenum cavity and then to the mechanical air handling system. This function is achieved by connecting an exhaust duct system to the top of the plenum chamber. Variable flow is obtained by employing a centrifugal blade-type blower powered by an adjustable-speed, permanent-magnet DC motor. The DC motor is operated by a motor controller that provides a full range of RPM control. The ducting system consists of a 6-in. (I.D.) PVC pipe that runs horizontally 18 ft and terminates at the controlled mechanical system. Volumetric air flow was measured by a differential pressure meter with a standard square edge orifice plate [3]. Pressure taps at the orifice plate were connected to a variable-reluctance pressure transducer and a transducer indicator. Flow rate was determined using the measured pressure difference and temperature of the return air.

Electrical Instrumentation: Input power for lamps and ballasts was measured with a calibrated watt transducer. The input voltage was monitored and held constant at 120 VAC with a voltage stabilizer.

Photometric Instrumentation: Throughout each simulation, changes in light output from the luminaire were monitored with a color-corrected photometer. The detector is mounted below the center of the luminaire in a cylindrical baffle that controls the solid angle of view and eliminates extraneous light.

Plenum Static Pressure Measurement: Static pressure within the plenum chamber was measured with a piezometer ring connected to an inclined draft gauge calibrated in inches of water. This measurement provides a comparative metric for field measurements of air flow in luminaire applications.

Data Acquisition System: Temperature, electrical, and photometric data were taken at controlled intervals with an automatic data acquisition system. Data were stored on a disc that was later accessed by support programs that provided for data reduction and processing.

Luminaire Configurations

Eight luminaire configurations were tested. Standard two-lamp CBM ballasts and 40-watt, F-40, rapid-start lamps were used throughout these tests. All the luminaire configurations in these tests were lay-in troffers with prismatic lenses, supported on a NEMA-G type ceiling system. All the lay-in configurations were sealed at the ceiling support/luminaire interface. This was done to insure that only direct compartment extract occurred under air flow conditions. The following configurations were tested:

1. Two-lamp luminaire: a standard non-air-flow fixture without slots or extract vents.

2. Two-lamp air-flow luminaire: a standard fixture having side slots and extract vents. This configuration was tested statically without plenum or lamp compartment extract.

3. Two-lamp air-flow luminaire (20 cfm): a fixture having lamp compartment extract only, at a volumetric flow rate of 20 cfm.

4. Two-lamp air-flow luminaire (50 cfm): a fixture having lamp compartment extract only, at a volumetric air-flow rate of 50 cfm.

5. Four-lamp luminaire: a standard non-air-flow fixture, without side slots or extract vents.

6. Four-lamp air-flow luminaire: a fixture having side slots and extract vents. This configuration was tested statically without plenum or lamp compartment extract.

7. Four-lamp air-flow luminaire (20 cfm): A fixture having lamp compartment extract only, at a volumetric flow rate of 20 cfm.

8. Four-lamp air-flow luminaire (50 cfm): a fixture having lamp compartment extract only, at a volumetric flow rate of 50 cfm.

Experimental Results

Figures 3 through 5 illustrate the dynamic changes that take place in a fixture as it approaches thermal equilibrium. Figure 3 shows how MLWT and light output vary as a function of time for a four-lamp luminaire test. Results illustrate the functional dependence of light output on the MLWT of a F-40 lamp/ballast system.

The luminaire is operated without air flow until temperature conditions stablize (four hours), at which point the return air system is activated to draw 50 cfm through the lamp compartment. Plenum extract slots were sealed for this test in order clearly to identify flow effects. The luminaire is then run with air flow until temperature conditions, specifically MLWT, stablize. Total duration of the test was seven hours.

The data show a rapid increase in MLWT and a corresponding reduction in light output when the luminaire is first energized. The MLWT realizes an asymptotic limit of 53.5°C after roughly 4 hours, at which temperature the lamps operate at about 83% of their maximum output (obtained at 25°C free air conditions). The activation of the air flow compartment extract system produced a rapid reduction of MLWT and a corresponding increase in light output. Under air flow conditions (50 cfm through lamp compartment), the luminaire stabilizes with an MLWT of 33.8°C. At this MLWT the lamps are operating at nearly their maximum output at 25°C free air conditions.

The reduction in MLWT is a direct function of the cooling effect facilitated by drawing 25°C room air into the compartment and then into the plenum and exhaust system. Figure 4 shows how MLWT and efficacy vary as a function of time for the four-lamp luminaire test. (Efficacy is expressed relative to the performance of the lamps at 25°C free air conditions.) As MLWT increases, both light output and system power decline correspondingly. This reduction lowers efficacy to about 92% at a stabilized MLWT of 53°C. Under air flow conditions, MLWT declines rapidly, producing an increase in both light output and system power and resulting in an increase in efficacy that approaches the optimum for the lamp/ballast combination tested. Figure 3 shows that employing a return air function can significantly reduce the operating MLWT and therefore increase the light output of the lamp/ballast system. This apparatus can be used to optimize air flow configurations for a specific luminaire application condition, as demonstrated in Fig. 5. Figure 5 illustrates the

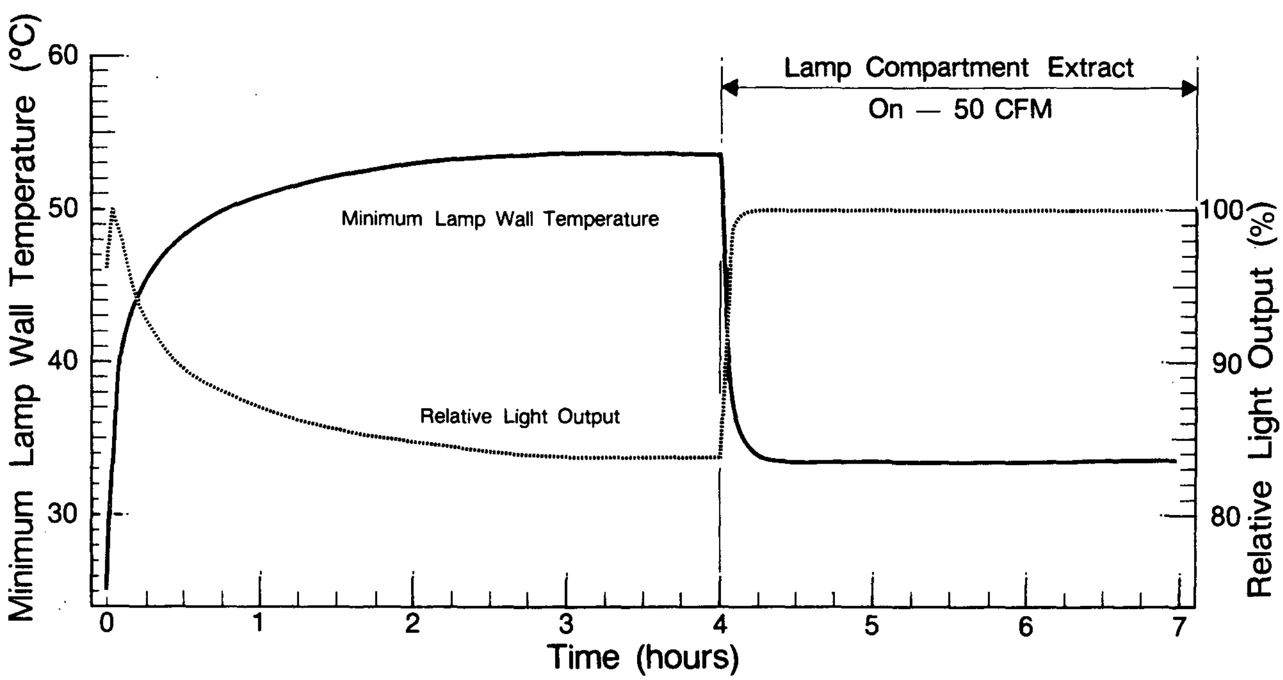


Fig. 3. MLWT and relative light output vs. time for the four-lamp air-flow luminaire.

variation in MLWT as a function of different air flow rates through the lamp compartment (20 cfm and 50 cfm).

Both air flow rates produce the same characteristic reduction in MLWT compared to non-air-flow configuration. At 20 cfm lamp compartment extract, the luminaire stabilizes at an MLWT of 39.7°C, approximately 6°C higher than the stablized MLWT at 50 cfm. This is directly a function of the efficiency of the air flow system's heat removal, which is dependent on the relative flow rate.

Figure 6 shows the change in relative light output as a function of MLWT for two F-40 lamps operating with a standard core-coil CBM ballast. These data were obtained using a temperature-controlled luminous flux integrator and the same lamp/ballast system as used in the luminaire tests [4]. The luminous flux integrator is an experimental apparatus for measuring the photometric and electrical performance of fluorescent light sources over a range of lamp wall temperatures. Performance data obtained from this apparatus typically are expressed as light output or efficacy as a function of MLWT. The measured operating MLWTs for each configuration tested using the luminaire/plenum/HVAC simulator are included on this lamp/ballast performance curve. These points show relative light output as a function of luminaire type and application condition.

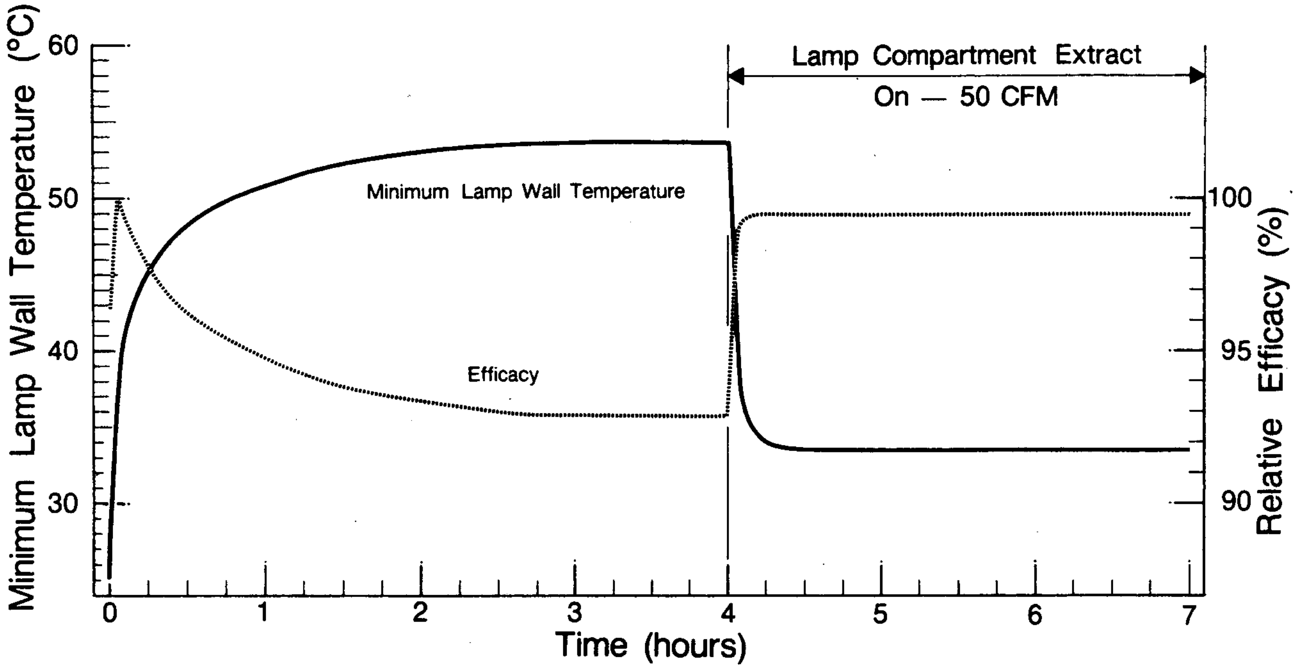


Fig. 4. MLWT and relative efficacy vs. time for the four-lamp air-flow luminaire.

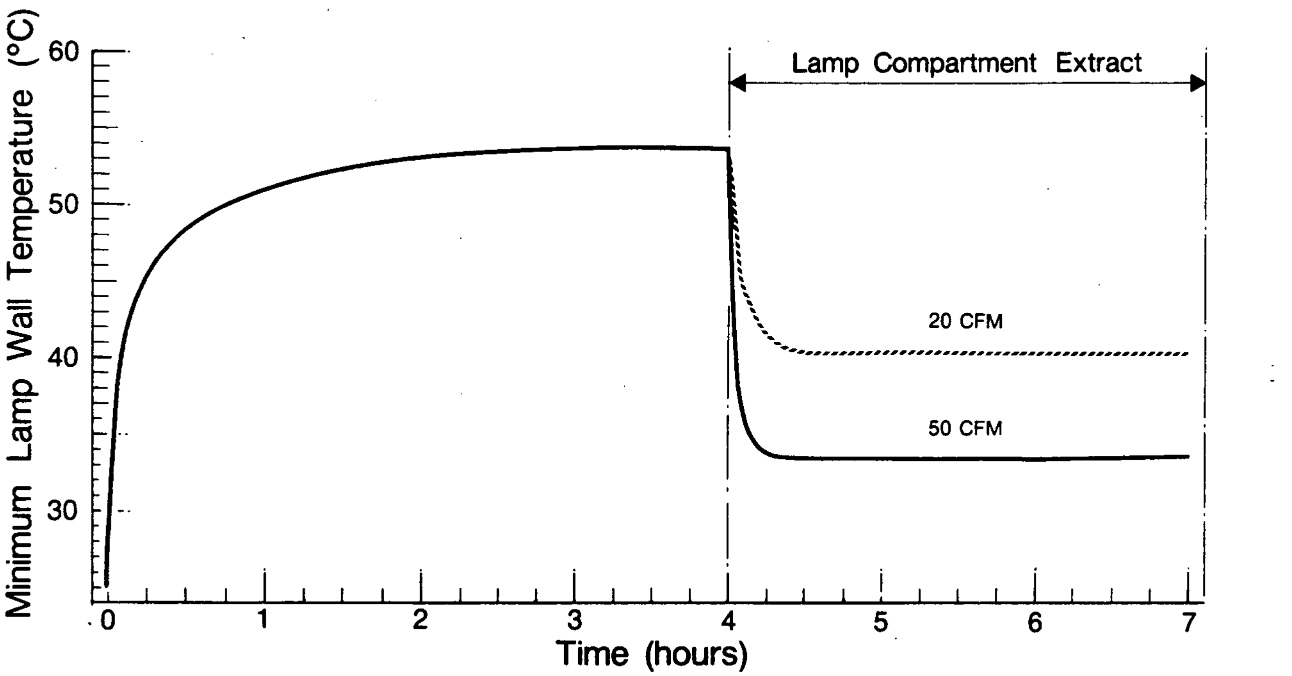
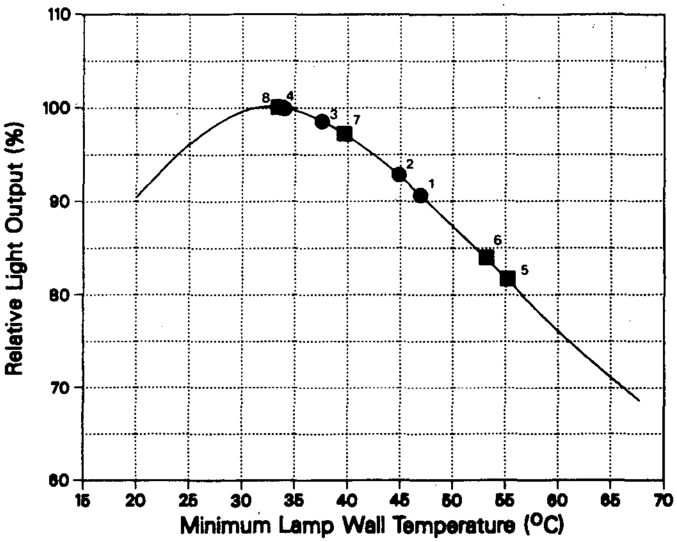


Fig. 5. MLWT vs. time for the four-lamp air-flow luminaire (20, 50 cfm).



1 - Two-lamp non-air-flow luminaire
2 - Two-lamp air-flow luminaire (static)
3 - Two-lamp air-flow luminaire (20 cfm)
4 - Two-lamp air-flow luminaire (50 cfm)
5 - Four-lamp non-air-flow luminaire
6 - Four-lamp air-flow luminaire (static)
7 - Four-lamp air-flow luminaire (20 cfm)
8 - Four-lamp air-flow luminaire (50 cfm)

Fig. 6. **Relative light output vs. minimum lamp wall temperature for F40 lamps operated by a CBM core-coil ballast.**

The static and non-air-flow luminaire configurations show the highest MLWTs and therefore the greatest reductions in light output. The difference in MLWT between similar configurations is a function of the number of lamps in each luminaire. The non-air-flow luminaire configuration typically runs 8°C hotter with four lamps than with two. Light output varies directly as a function of the number of lamps, in this case by 10%. This variation in light output also exists to a smaller degree between the two-lamp/four-lamp air flow configuration.

Of the luminaire configurations tested (two-lamp and four-lamp), those that employ a lamp compartment extract flow rate of 50 cfm have the lowest operating MLWTs and the highest light output. The return air function could lower the MLWT below optimum, thereby reducing light output; this would be a function of room air temperature and extract rate.

Table 1 presents the luminaire test results, including operating MLWT and relative light output (expressed in terms of the performance obtained at 25°C free air conditions).

Discussion

The results demonstrate the usefulness of the apparatus in generating MLWT data for a range of luminaire types and application conditions. This MLWT data can be used to determine parametrically how the specific luminaire and application parameters affect lamp/ballast performance.

Initial experiments show that the reduction in light output can approach 20% for a typical luminaire operating under static conditions. Employing a return air function lowered the operating MLWT so that the lamps provided nearly optimal performance. It should be noted that these experiments with air-flow configurations were conducted with a room air temperature of 25°C, which is somewhat warmer than typical office conditions. Employing a return air function with cooler room air temperatures may produce an operating MLWT that is lower than optimum. This is an especially important consideration when employing low-wattage lamps, which are more sensitive to MLWTs at below 35°C than are the standard F-40s. Optimizing lamp/ballast performance therefore would require a careful study of the luminaire system hardware and the application conditions, specifically room air temperature.

Lamp performance was shown to be affected by fixture type, specifically the number of lamps and construction. First, under static or non-air-flow conditions, there is approximately a 10% difference in lamp light output between the two-lamp and four-lamp luminaire. This is a direct function of the higher operating MLWT for the four lamps, which produce a higher lamp compartment temperature than does the two-lamp fixture. This difference between two-lamp and four-lamp fixtures can also be seen in typical coefficient-of-utilization tables.

TABLE 1

Luminaire Configuration	Stablized MLWT (°C)	Relative Light Output (%)*
Two-lamp, non-air-flow luminaire	47.0	91.2
Two-lamp, air-flow luminaire (static)	44.9	93.4
Two-lamp, air-flow luminaire (20 cfm)	37.7	98.6
Two-lamp, air-flow luminaire (50 cfm)	34.0	100
Four-lamp, non-air-flow luminaire	55.1	82.4
Four-lamp, air-flow luminaire (static)	53.5	84.1
Four-lamp, air-flow luminaire (20 cfm)	39.7	97.8
Four-lamp, air-flow luminaire (50 cfm)	33.8	100

* Expressed as a percent of the light output at 25 °C Free air Conditions.

Secondly, a small performance variation is seen between the non-air-flow luminaire and the air-flow luminaire under static conditions. This is directly a function of the difference in construction between the two fixture types. The air-flow luminaire employs a series of vents and controlled slots that facilitate air flow through the lamp compartment under mechanically induced pressure conditions within the plenum. These openings allow for a limited amount of natural convection to occur even without forced air flow. This convection results in a slightly cooler lamp compartment temperature and MLWT. This natural venting would suggest an advantage in providing openings in fixture types where air flow is not employed. In building designs that cannot accommodate an integrated return air function, employing open luminaires will produce lower operating MLWTs than will enclosed luminaires. Conversely, building applications having relatively low room air temperatures might call for an enclosed luminaire in order to maintain an optimum MLWT.

The luminaire configuration and application conditions tested represent a small subset of possible combinations. Future research will be directed at detailed examination of:

1. A wide cross section of fixture types and mounting configurations.

2. A range of lamp/ballast combinations including low-wattage lamps and high-frequency ballasts.

3. A representative range of room air temperatures.

Conclusions

A controlled technique and flexible experimental apparatus have been developed to measure the operating MLWTs of a range of luminaire types and application conditions. The performance results obtained from the luminaire/plenum/HVAC simulator underscore the importance of understanding how application conditions affect the operating MLWTs and therefore the light output and efficacy of the lamp/ballast system.

Specifically, elevated MLWTs were measured under typical application conditions, which reduced light output from the optimum by almost 20%. We studied lamp compartment extract techniques that reduced MLWT, allowing the lamp/ballast combinations to perform near optimum.

The measured variability in lamp performance, as a function of the luminaire application conditions tested, clearly indicates that specified illuminance requirements will be met only if the lighting designer accounts for the effect of MLWT in the lighting design process.

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