Integration of HVAC system and LED Based Luminaires

Ke Li
July 2013
Msc Thesis
Eindhoven University of Technology
Master Thesis

The Integration of HVAC System and LED Based Luminaire

July 2013

Student: Ke Li
Building Physics and Services
ID: 0786963

Supervisors
Prof.dr.ir. J.L.M. Hensen
Dr. D. Cóstola
Dr. ir. M. Mirsadeghi (External)
Dr. ir. T. Treurniet (External)

Faculty: Architecture, Building & Planning
Eindhoven University of Technology
CONTENT

Part I: Impacts of Artificial Lighting Retrofit using LED on the Heating Ventilation and Air-conditioning System (HVAC) and Energy Saving Potential of HVAC-LED Integration in Commercial Buildings

One important challenge to present building industry is to reduce building energy demand. Retrofit artificial lighting is one of the most effective measures to reduce building lighting energy demand. Light-emitting-diode (LED) technology is increasing popularity in building lighting retrofit. However, except less electricity consumption, lighting retrofit has also secondary effect on building heating, ventilation and air-conditioning (HVAC) system consumption. Based on existing studies on lighting-HVAC interaction, this research introduced LED lighting –HVAC interaction into this scope. Furthermore, unlike conventional lighting technology, high LED junction temperature ($T_J$) will lead to reliability problem and cause failure. Cooling LED is one of the primary issues in LED product development. Therefore in addition to normal LED retrofit, this research also proposed a new concept to cool LED by using HVAC ventilation system flow. This is defined as integrated HVAC-LED. The increasing convective flow around HVAC-LED will not only decrease LED junction temperature, but will also increase LED lumen output. This integration will result in higher lighting efficiency, less lighting energy consumption and, repeatedly, HVAC system energy consumption changes. This part investigated the impact of LED and HVAC-LED retrofits on building energy demand changes, and the impact on LED thermal management.

Part II: Impacts of Suspended Ceiling Configuration to the Lighting Thermal Energy Gain to Conditioned Space

In part I, in order to calculate the thermal energy gain from lighting to space cooling demand, an assumption is made that 100% of the lighting thermal energy will be added to conditioned space; regardless of the configuration of suspended ceiling. This part introduced how changing ceiling configurations will or will not affect the lighting thermal energy gain.

Part III: Experiment: Relation between Duct Face Velocity and HVAC-LED Junction Temperature and Efficacy

This part intents to validate the relation between changing air velocity and HVAC-LED junction temperature; and the relation between changing air velocity and HVAC-LED relative lumen output, as calculated in Part I through lab experiment.

Part IV: Dedicated Ceiling Concept and Simulation

The dedicated ceiling concept refers to the ceiling which is able to utilize thermal energy from HVAC-LED during winter, and extract the energy during summer, for energy saving purpose. A serious of computer simulations have been performed to exam the energy saving potential of such concept.
I. Impacts of Artificial Lighting Retrofit using LED on the Heating Ventilation and Air-conditioning System (HVAC) and Energy Saving Potential of HVAC-LED Integration in Commercial Buildings
Impacts of Artificial Lighting Retrofit using LED on the Heating Ventilation and Air-conditioning System (HVAC) and Energy Saving Potential of HVAC-LED Integration in Commercial Buildings

Ke Li\textsuperscript{a}, D. Cóstola\textsuperscript{a}, Mohammad Mirsadeghi\textsuperscript{b}, J.L.M. Hensen\textsuperscript{a}, Theo Treurniet\textsuperscript{b}

\textsuperscript{(a) Building Physics and Services, Eindhoven University of Technology, the Netherlands}
\textsuperscript{(b) Royal Philips Electronics N.V.}

Abstract

One important challenge to present building industry is to reduce building energy demand. Retrofit artificial lighting is one of the most effective measures to reduce building lighting energy demand. Light-emitting-diode (LED) technology is increasing popularity in building lighting retrofit. However, except less electricity consumption, lighting retrofit has also secondary effect on building heating, ventilation and air-conditioning (HVAC) system consumption. Based on existing studies on lighting-HVAC interaction, this research introduced LED lighting –HVAC interaction into this scope. Furthermore, unlike conventional lighting technology, high LED junction temperature ($T_j$) will lead to reliability problem and cause failure. Cooling LED is one of the primary issues in LED product development. Therefore in addition to normal LED retrofit, this research also proposed a new concept to cool LED by using HVAC ventilation system flow. This is defined as integrated HVAC-LED. The increasing convective flow around HVAC-LED will not only decrease LED junction temperature, but will also increase LED lumen output. This integration will result in higher lighting efficiency, less lighting energy consumption and, repeatedly, HVAC system energy consumption changes. The method of the research first studied the HVAC-LED junction temperature change in response to ventilation face velocity change by using empirical calculation; then the interactions between HVAC and LED are calculated using coincidence factor (CF) method. Tubular fluorescent light T8 is used before retrofit. Due to the similar calculation method for LED and integrated HVAC-LED, both used CF method. Five different commercial building functions in six various climate types are included in this scope. As results, the junction temperature of HVAC-LED has been reduced effectively as ventilation duct face velocity increases. For RGB based LED, this means a great potential to reduce lighting power density, and furthermore annual lighting electricity energy
demand. The reduction varies from 6% to 40% comparing to T8 lighting system, which depends on type of building functions. As comparison, the reduction of replacing T8 system with non-integrated LED is 5-33%, which is less however insignificant. Both HVAC-LED and LED replacements to T8 show savings on cooling energy and penalties on heating energy. In general warm climates save more cooling energy; and cool climates suffer more heating energy penalties. The differences between HVAC-LED and LED do not have large differences.

**Keywords:** Light Emitting Diode, HVAC system, Integration, Coincidence Factor, Building Energy Consumption

1 Introduction

Lighting energy consumption takes up 17% to 33% in commercial building sectors [1, 2], which counts for the second largest energy end-use after space heating and cooling [3]. For existing commercial building, lighting retrofit is one of most effective measures to reduce building energy consumption. Lighting retrofit means to replace an old-type lighting fixture with a new type fixture. Light Emitting Diode (LED) has rapidly growing its popularity in the retrofit market [4] due to its high energy efficiency, long useful lifetime and environmental benefits related to its material and production process [5-9]. However reductions in lighting energy also have secondary effects on building’s heating and cooling energy demands. Researches have been done both empirically and by computer simulations to evaluate the interactions between lighting and heating, ventilation and air-conditioning (HVAC) energy demands [10-15]. In general, lighting retrofits increase heating and decrease cooling energy demands of a building; consequently affect the sizes of building HVAC system. However, these effects have not been studied for LED retrofits. The effects should be more significant than other luminaire types, because LED has no infrared radiation (IR) emission[16] as well as much reduced thermal gain to conditioned space.

Furthermore, although LED has less thermal gain to conditioned space than other types of luminaires, the cooling of LED’s P-N junction is a prior research topic in LED industry: high junction temperature (T_J) of LED will lead to reliability problems such as short lifetime, wavelength shift, low luminous flux efficiency and even catastrophic failure [16, 17]. In general LED T_J ranges between 60°C to 85°C, and can be even higher than 100°C[16]. Since luminaires and HVAC ventilation ducts usually share the same space in commercial building’s suspended ceiling, there is potential to utilize the ventilation duct’s air flow to pick up LED’s thermal gain for ‘free’ and to reduce LED junction temperature. This combination of HVAC system and LED is proposed as
HVAC-LED integration in this research. Although on market such integrated ‘fan-light combi’ can be found [18-21], the designs are purely for aesthetics purpose, and have not been used for LEDs. The impacts of such product to the building system energy demands have not been studied scientifically. Thus in addition to the study of LED retrofit to HVAC energy demand changes, the study of integrated HVAC-LED to HVAC energy demand changes is also included in this research. The HVAC-LED is expected to have even lower thermal gain to the conditioned space, because when LED is cooled, its efficacy as well as energy demand will reduce. The energy demand of LED will be converted to visible light and heat, which are used for calculating LED thermal gain.

The objectives of this research are the followings:

- Quantify the impacts of LED retrofit onto building heating, cooling and electricity energy demands.
- When using HVAC airflow to remove LED’s convective and conductive thermal gain, calculate the HVAC-LED junction temperature’s reduction and calculate the HVAC-LED efficacy improvement.
- Quantify the impacts of integrated HVAC-LED onto building heating, cooling and electricity energy demands.

The study uses white-light tubular LED as replacement of tubular fluorescent light T8. LEDs are recessed on suspended ceiling. There are two different principles of white-light emitting technology scoped: RGB system and blue/UV-phosphor (Phosphor based LED) system. Because RGB based LED and Phosphor based LED have different luminous flux sensitivity to junction temperature changes, this study include both types of LED. In general RGB based LED is more sensitive than phosphor based LED, which means when $T_j$ is reduced, RGB based LED increases more percentage of luminous flux than phosphor based LED. The calculation of these two types LED will be further explained in methodology section. In order to provide an overview of how LED or integrated HVAC-LED will affect building’s heating, cooling and lighting energy demand, the scopes of calculation include five prototypical commercial building functions (large office, restaurant, supermarket, school and hotel) and in six typical climates (very hot, hot warm, mixed, cool and cold).

2 Methodology

Methodology of this research consists of three main topics:

1. The changes of efficacy of integrated HVAC-LED in response to various air velocities provided by HVAC system.
2. The reduction thermal gain to space (characterized by changes of lighting power density, ΔLPD) of retrofitting from T8 to LED and from T8 to HVAC-LED. The calculation methods for both LED and HVAC-LED here are similar, they will be combined explained.

3. The calculation of heating and cooling energy demand based on ΔLPD, Sezgen and Koomey’s coincidence factor [22] and DOE commercial reference building simulation results [23].

The overall methodology is shown in Figure 2-1.

**Figure 2-1. Overview of methodology**

**2.1 Efficacy Changes of Integrated HVAC-LED**

Efficacy changes are calculated according to HVAC-LED junction temperature (Tj) changes, which include both RGB-based and phosphor based types of LED. The junction temperature changes are calculated by a simplified thermal network representing HVAC-LED heat transfer scheme.

**2.1.1 Thermal Network and Calculation of Tj**

In this study, luminaires are recessed in ceiling plenum. Ceiling plenum acts as return air duct of HVAC system. Return air flow will pick up heat generated from HVAC-LED through openings on the housing. Figure 2-2 shows a possible scenario of the integration. Because this is an initial scoping study, specific details of the integrated fixture design is not considered.
Figure 2-2. A possible integration scenario of HVAC-LED

It is assumed that the return air passing through HVAC-LED has two representing air velocities: low value of 0.2 [m/s] and high value of 2.5 [m/s]. The HVAC-LED thermal energy removed by the return air is assumed to add to HVAC thermal loads; because in general air temperatures between suspended ceiling plenum and room space do not differ significantly [24], the return air plenum constantly exchange heat with room space.

Figure 2-3. HVAC-LED heat transfer scheme (left figure) and thermal network (right figure)

**Figure 2-3** illustrates heat transfer scheme around HVAC-LED tube and its thermal network. Since heat removed by radiation and conduction of HVAC-LED are much smaller in comparison to convection, the thermal network is simplified, only thermal resistance of convection is calculated. The HVAC-LED is modelled as a long cylinder perpendicular to air flow. Diameter of the cylinder is 25.5 [mm], and the length is 1.2 [m]. The nominal power of LED is 26 [W], as equivalent to a nominal power of 32.5 [W] T8 with same luminous flux level [25]. The power conversion rate to visible light of a 100lm/w LED is about 32.2% (1lm white light = 0.003226W electric power, by SI definition of luminous flux). Thus the heat flux is 67.8% or 17.6 [W] of HVAC-LED. Heat flux of HVAC-LED is assumed always constant. Air temperature around luminaire is assumed 30 [°C]. Thermal conduction resistance of HVAC-LED including heat sink is assumed 3, for the whole fixture [K/W]. Thus the junction temperature of HVAC-LED can be calculated according to Eq. 1.
\[ T_j = q \times (R_{\text{LED}} + R_{\text{conv}}) + T_a \]  
\[ \text{Eq. 1} \]

Where \( q \) is the constant heat flux of HVAC-LED [W], \( R_{\text{LED}} \) is the thermal resistance of HVAC-LED including heat sink [K/W], \( R_{\text{conv}} \) is the convective transfer resistance around HVAC-LED [K/W], which can be calculated according to Eq. 2. \( T_a \) is the ambient temperature around HVAC-LED.

\[ R_{\text{conv}} = \frac{1}{Ah} \]  
\[ \text{Eq. 2} \]

Where \( A \) is the surface area of HVAC-LED \([m^2]\), \( h \) is convective heat transfer coefficient at HVAC-LED surface \([K/m^2W]\). \( h \) can be calculated according to Eq. 3.

\[ h = Nu \times \frac{A}{D} \]  
\[ \text{Eq. 3} \]

Where \( Nu \) is Nusselt Number [-], \( \lambda \) is air thermal conductive \([W/mK]\), \( D \) is HVAC-LED diameter \([m]\). \( Nu \) can be calculated according to imperial equation of cylinders in cross flow (Eq. 4). This equation is suitable when Reynolds Number ranges between 40 and 40,000, which fits to this calculation.

\[ Nu = 0.683Re^{0.466}Pr^{1/3} \]  
\[ \text{Eq. 4} \]

Where \( Re \) is Reynolds Number \([\text{dimensionless}]\), which can be calculated according to Eq. 5. \( Pr \) is Prandtl Number \([\text{dimensionless}]\), which is 0.7 constant when air temperature is between 0-180 [°C]. Eq. 4 can be used when the condition satisfies \( PrRe \gg 0.2 \).

\[ Re = \rho v D/\eta \]  
\[ \text{Eq. 5} \]

Where \( \rho \) is air density \([\text{kg/m}^3]\), \( v \) is air velocity \([\text{m/s}]\), \( \eta \) is dynamic viscosity of air \([\text{kg/(m*s)}]\). At 30 [°C] air temperature, \( \eta \) is \( 1.87 \times 10^{-5} \) [\text{kg/(m*s)}].

This study uses two different \( v \) values for calculating HVAC-LED new junction temperatures: 0.2 [m/s] and 2.5 [m/s]. When \( T_j \) decrease, lumen output of HVAC-LED will increase correspondingly; since the power input of HVAC-LED in this study assumed to be constant, the efficacy will also increase. Next part will explain method to calculate HVAC-LED efficacy change when integrated with HVAC system.

2.1.2 Efficacy Changes Calculation

The calculation of HVAC-LED efficacy change is based Figure 2-4 [16]. It describes the changes of relative lighting output in related to junction temperature \( T_j \) changes for various LED color sources. In this study, the RGB based white light LED is the ‘white’ dash line; while phosphor based LED is characterized by the ‘blue’ dash line.
The sensitivity of light output of RGB based LED to $T_j$ is higher than the one of phosphor based LED. From Figure 2-4, it is considered in this study that for RGB based LED, every decrease of 10 °C $T_j$ will result in 10% more luminous flux; while for phosphor based LED, every decrease of 10 °C $T_j$ will result 1% more luminous flux. Since the input electric power remains constant, the efficacy of HVAC-LED is only related to luminous flux output. The changes on luminous flux can be calculated by the changes of relative luminous flux output (%) indicated by Figure 2-4, which depends on the $T_j$ of HVAC-LED. According to the calculation method of $T_j$ under various air velocities, it is able to calculate HVAC-LED efficacy changes.

The HVAC-LED and LED efficacy is used to calculate lighting power density (LPD, [w/m²]) for different building function. LPD reflects the thermal energy gain from lighting to building, which is important to calculate building heating and cooling energy demands. Next section will introduce the calculation method of LPD.

2.2 Calculation of Fixture Lighting Power Density

Luminaire fixture’s lighting power density (LPD) will determine how much thermal energy will building HVAC system gains from lighting. A conservative estimation in this study is that 100% lighting thermal energy will be added to HVAC system thermal load. Regardless of the energy in suspended ceiling plenum that are picked up by return air duct and rejected outdoor. Eq. 6 shows the LPD calculation

$$LPD = \frac{E_{Building}}{K_{Fixture}}$$  \hspace{1cm}  \text{Eq. 6}

Where $E_{Building}$ is the average illuminance level [lm/m² or lux] of building, different building function has different illuminance level requirement, the specific calculation method is shown in Annex[Error! Reference source not found.]. $K_{Fixture}$ is the luminaire fixture efficacy [lm/w], which is calculated according to Eq. 7.
\[ K_{\text{Fixture}} = K_{\text{luminaire}} \times \eta_e \times \eta_r \] \hspace{1cm} \text{Eq. 7}

Where \( K_{\text{luminaire}} \) is luminaire’s efficacy [lm/w]; \( \eta_e \) is fixture efficiency, here uses the value of 0.7 for T8 and 0.85 for LED and HVAC-LED[26]. \( \eta_r \) is ballast the efficiency for T8 or driver efficiency for LED/HVAC-LED, here uses the value of 0.85 in all cases.

The building’s LPD from normal LED or HVAC-TLED, which resembles thermal energy gain from lighting, will need to subtract the LPD of T8 in order to calculate changes of lighting thermal energy load of HVAC system in retrofit. The acquired LPD reduction (\( \Delta \text{LPD} \)) is used to calculate heating, cooling and electricity energy demand in next section.

2.3 Calculation of Heating, Cooling and Lighting Electricity Energy Demand

Calculation method of heating, cooling and electricity energy demand through reduction of lighting power density (\( \Delta \text{LPD} \)) will be explained in this section. The usage of coincidence factor (CF) proposed by Sezgen and Koomey is also explained.

2.3.1 Calculation of Heating, Cooling and Lighting Energy Demand

The study combine reference energy data and calculated energy reductions which are resulted from reduction of LPD to calculate total energy demand after lighting retrofit (see Eq. 8). The reference data is based on commercial reference building model developed by the DOE [23]. The building model utilized statistical data from Energy Information Administration (EIA) Commercial Building Energy Consumption Survey (CBECS) as input[28]. The results of the reference building energy demand are obtained from simulation software EnergyPlus performed by DOE. Lighting power density of the reference buildings can be considered as using T8 equivalent system, because the LPD of reference building has 9w/m² on average which is close to the LPD of using T8. T8 also has the largest usage percentage among all luminaire types for general [29].

\[
\text{Total Energy Demand} \hspace{1cm} \text{Eq. 8}
\]

\[
= \text{Reference Energy Demand} + \text{Changes of Energy Demand (Calculated)}
\]

The calculation of changes of energy demand is based on coincidence factors (CF), which will be explained in next section.
2.3.2 Coincidence Factors

The term coincidence factors (CF) were introduced by Sezgen and Koomey in order to study the impact of lighting retrofit to HVAC heating and cooling energy demand [12, 13]. Coincidence factors used in this study include lighting conservation load factor (CLF), annual heating CF, annual cooling CF, heating demand CF and cooling demand CF.

All Coincidence factors are dimensionless. The CLF refers to the ratio between reduction of annual lighting energy use [kWh/m²] and the reduction of every 1 [kW/m²] of lighting power density (LPD). Heating CF or cooling CF describes the ratio between changes of annual heating/cooling energy and changes of annual lighting energy. The CF were obtained by using computer simulation software DOE-2 in their research: varying the LPD level to 2/3 of its original level of a commercial building model and recording the changes of annual lighting energy and annual heating/cooling energy demands. Building functions, building geometries, schedule profiles and HVAC settings, climate profiles, etc. were based on a U.S national scale survey of prototypical commercial buildings [27].

This study used CFs from 5 prototypical building and 6 climates, which are listed in Table 2-1.

Table 2-1. Prototypical commercial building and climates selected in this study, typical international city of specific climate is also given as example.

<table>
<thead>
<tr>
<th>Climate/Building Functions</th>
<th>Very Hot Miami</th>
<th>Hot Phoenix</th>
<th>Warm San Francisco</th>
<th>Mixed Paris</th>
<th>Cool Amsterdam</th>
<th>Cold Stockholm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large Office</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Restaurant</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Supermarket</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Secondary School</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Large Hotel</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Previous section has introduced the calculation method of LPD. T8 is used as reference luminaire for retrofit. The changes of LPD (ΔLPD) between retrofit from T8 to LED and from T8 to HVAC-LED are recoded. By multiplying ΔLPD and corresponding CFs of certain building function and climate, it is able to obtain annual heating/cooling energy demand reduction.

3 Results and Discussions

Based on the methodology described in last section, this section firstly shows the calculated results of integrated HVAC-LED efficacy changes under various air velocities; then the reductions of lighting power
density (LPD) as a result from retrofits are shown, both for LED and HVAC-LED retrofits; lastly the heating, cooling and lighting energy demands per building functions as consequences of LPD changes are provided.

3.1 HVAC-LED Efficacy and Lighting Power Density Changes Due to Velocity Changes

The calculated results of junction temperature according to section 2.1.1 are shown in Figure 3-1. $T_j$ of HVAC-LED decreases tremendously at low air velocity, and then the decrease is not significant when the velocity increases further. The results shows consistency with similar study [31].

![Figure 3-1](image_url)

Figure 3-1. Calculated LED junction temperature decrease caused by forced convection from vertical air flow.

The efficacies of HVAC-LED are calculated based on new junction temperature, as described in section 2.1.2 (see Figure 3-2). The efficacy of LED of 100 [lm/w] under free convection (0.05m/s velocity) is used for comparison.

![Figure 3-2](image_url)

Figure 3-2. Results of efficacies of RGB based LED and Phosphor based LED in free convection and forced convection air flow.
When air velocity is under free convection condition (0.05 m/s), the changes of efficacy of both phosphor based and RGB based LED can be neglected. When air flow velocity increases further, the efficacy of RGB based LED shows higher improvement than phosphor based LED. Since no significant efficacy improvement of phosphor based LED is observed, the results of phosphor based LED will be excluded later on. The new efficacy results of RGB based HVAC-LED are used for calculating LPD, which are described in section 2.2. Table 3-1 shows the result of LPD of both HVAC-LED, LED and T8 per building function.

Table 3-1 Calculated LPD of T8, LED and HVAC-LED for all building functions

<table>
<thead>
<tr>
<th>Building Function</th>
<th>Lighting Power Density [w/m²]</th>
<th>Free convection 0.05 [m/s]</th>
<th>0.20 [m/s]</th>
<th>2.50 [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T8</td>
<td>LED</td>
<td>HVAC-LED</td>
<td>HVAC-LED</td>
</tr>
<tr>
<td>Secondary School</td>
<td>9.1</td>
<td>6.0</td>
<td>5.6</td>
<td>5.0</td>
</tr>
<tr>
<td>Large office building</td>
<td>8.8</td>
<td>5.8</td>
<td>5.4</td>
<td>4.8</td>
</tr>
<tr>
<td>Large Hotel</td>
<td>7.5</td>
<td>5.0</td>
<td>4.6</td>
<td>4.1</td>
</tr>
<tr>
<td>Restaurant</td>
<td>6.6</td>
<td>4.1</td>
<td>3.9</td>
<td>3.4</td>
</tr>
<tr>
<td>Supermarket</td>
<td>6.0</td>
<td>3.9</td>
<td>3.7</td>
<td>3.3</td>
</tr>
</tbody>
</table>

For all building function categories, T8 has the highest LPD level. The LPD decreases when the convective air velocity cross HVAC-LED increase. For different building types, secondary school has the highest LPD, and the supermarket has the lowest value. Next section will show results of lighting, cooling and heating energy demands which are calculated based on LPD and coincidence factor (CF).

3.2 Lighting Electricity Demand Before and After Retrofit by Building Function

The calculated lighting electricity demands of LED and HVAC-LED retrofits are shown in Figure 3-3. HVAC-LED electricity consumption is the average value of LED under 0.2m/s and 2.5m/s air velocity; the deviation of the low and high velocity is less than 1, therefore only the average value is shown. This applies to all the following results.
In general all building functions show reduction of annual lighting energy demand after retrofit from T8 to LED. Depending on specific building function, the savings range from 8 to 16 [kwh/m²/yr], or 5% to 33% per m² annually. The integrated HVAC-LED shows more savings compare to LED, which ranges from 10 to 20 [kwh/m²/yr], or 6%-40% per m² annually, both are compared to T8 lighting system. The buildings have high lighting electricity demand intensity in general have lower savings in percentage; this is because such buildings (e.g. restaurant and supermarket) have relatively low surface area, when the lighting energy is calculated on per square meter basis the resulting energy intensity is higher than buildings with large surface area.

### 3.3 Heating and Cooling Energy Demand of Large Office Building before and after Retrofit

Due to the large amount of data, only the results of heating and cooling energy demand from large office building are discussed into details (see Figure 3-4). The energy demands of the rest of building functions and climates share the same trends as large office building; therefore they are not discussed separately into details.
An overview of changes of energy demand for all building functions and climates is provided in Figure 3-5.

![Figure 3-4](figure.png)

In general in hot climate regions the large office building demands more cooling energy and in cold climate regions it demands more heating energy. The retrofits from T8 to both LED and integrated HVAC-LED reveal penalties on heating energy demands and savings on cooling energy demands. The maximum heating penalties are 14-18% and the maximum cooling savings are 12-14%. This is because such retrofits reduce the amounts of lighting power density inside buildings, which can be considered as lighting internal heat gain. For the integrated HVAC-LED, it can also be observed that the retrofit results in more heating penalty and higher cooling savings compare to LED retrofit. For example, the maximum cooling energy savings of HVAC-LED retrofit is 14% in cold climate, and for LED retrofit is 12%. These results are expected because the integration of LED to HVAC increases LED efficacy and further reduce lighting power density. However, the changes in percentage between LED retrofit and HVAC-LED retrofit are not significant.

3.4 Heating Energy Demand Penalty and Cooling Energy Demand Saving by Building Function and Climate

An overview of changes of heating and cooling energy demand in five building functions and six climates is provided in Figure 3-5. Under each building function, there are two subcategories for both LED retrofit and
HVAC-LED retrofit. The energy savings for cooling are shown as negative value in green bars; and the energy penalties for heating are shown as positive value in red bars. The amount of heating and cooling energy changes are climate dependent: in very hot climate, there is no heating penalties because heating energy is not demanded and a reduction of lighting internal heat gain will not affect heating energy demand. As it comes to colder climate regions, the heating energy penalties increase correspondingly, because less heat gain from LED can contribute to ‘free heating’ energy. The maximum heating penalty is for restaurant building of 9 [kwh/m2/yr].

On contract, the cooling energy reductions also depend on climate. In general cooling energy reductions can be observed for all climate regions including cold climate, this is because commercial buildings usually have high internal gain from occupants and equipment all year round. The warmer the climate the more reductions of cooling energy will happen. Maximum reduction of cooling energy is 19 [kwh/m2/yr] for supermarket.

<table>
<thead>
<tr>
<th>Building Function</th>
<th>Supermarket</th>
<th>Restaurant</th>
<th>Large Office</th>
<th>Hotel</th>
<th>School</th>
</tr>
</thead>
<tbody>
<tr>
<td>Retrofitted Type</td>
<td>LED Retrofit</td>
<td>HVAC LED Retrofit</td>
<td>LED Retrofit</td>
<td>HVAC LED Retrofit</td>
<td>LED Retrofit</td>
</tr>
<tr>
<td>Climate/Changes of Energy Demand</td>
<td>Cooling</td>
<td>Heating</td>
<td>Cooling</td>
<td>Heating</td>
<td>Cooling</td>
</tr>
<tr>
<td>Very Hot</td>
<td>-16</td>
<td>1</td>
<td>-14</td>
<td>0</td>
<td>-14</td>
</tr>
<tr>
<td>Hot</td>
<td>-14</td>
<td>1</td>
<td>-14</td>
<td>0</td>
<td>-12</td>
</tr>
<tr>
<td>Warm</td>
<td>-14</td>
<td>4</td>
<td>-13</td>
<td>3</td>
<td>-13</td>
</tr>
<tr>
<td>Mixed</td>
<td>-10</td>
<td>5</td>
<td>-12</td>
<td>8</td>
<td>-10</td>
</tr>
<tr>
<td>Cool</td>
<td>-10</td>
<td>6</td>
<td>-12</td>
<td>9</td>
<td>-12</td>
</tr>
<tr>
<td>Cold</td>
<td>-9</td>
<td>6</td>
<td>-12</td>
<td>9</td>
<td>-9</td>
</tr>
</tbody>
</table>

Figure 3-5. Changes of heating and cooling energy demand of LED and HVAC-LED retrofits, for five commercial building functions and six climates. The calculation method is explained in section 2.3.

Types of building also affect the amount of heating penalties and cooling savings. The largest differences between the highest and the lowest changes are 11 [kwh/m²], among supermarket and school building, which is insignificant change for annual energy demand. Compare to LED retrofit, the HVAC-LED in general shows more savings on cooling energy (from 1 to 3 [kwh/m²] for very hot climate) and more penalties on heating energy (from 1to 2 [kwh/m²] for cold climate). The differences between LED and HVAC-LED are also quite small, because both of the luminaire types have already high efficacy. These results imply that the upgrading from LED to HVAC-LED will have vital impacts on the building heating and cooling energy demand changes.

4 Discussion
As indicated by the results, warmer climates have more energy saving potential than colder climates when higher energy efficient lighting is retrofitted. HVAC-LED shows further energy reductions. The amount of energy saving dependent on various factors such as climate region, HVAC system setting, building configurations, etc. In reality these factors will deviate from the benchmark settings, therefore the uncertainties need to be discussed.

This study assumed that luminaires are installed on suspended ceiling. The thermal energy extracted from luminaires will eventually be added to HVAC cooling load by 100%, regardless of the thermal energy picked up by return air duct which will be extracted outdoor. In reality, this percentage of thermal energy from lighting being conditioned by HVAC system depends on the presence of economizer; the height and the thermal properties of suspended ceiling. In order to test how different suspended ceiling will affect lighting thermal energy gains, a series of computer simulations are performed (see Part II). Four suspended ceiling set-ups which have different height and R-value are modeled for a typical large office building. The simulations are performed in all six climates. As comparison, the same building using plain ceiling set-up is also modeled. This is because in plain ceiling set-up all the lighting thermal gain will be added to cooling energy load. As results, the heating and cooling energy demands among plain ceiling and suspended ceiling set-ups have differences of no more than 4.9% (3.2kwh/m²). The average difference is subtle at 4.1% (2.5kwh/m²). This means that the variance of suspended ceiling set-up does not differ too much from plain ceiling; and the assumption of 100% lighting thermal energy is added to cooling load is valid. Although the presence of using economizer is not discussed, the usage of economizer will reduce the lighting thermal energy added to cooling load, which as a result will further reduce the impacts on heating and cooling energy changes.

While studying the duct face velocity impacts on HVAC-LED junction temperature, another assumption is made that the ambient air temperature is 30°C around luminaire. This value may vary in reality, so does the junction temperature of HVAC-LED. However the reduction of junction temperature ($\Delta T_j$) will not change significantly. This is because $\Delta T_j$ is mainly depended on convective heat transfer coefficient (see Eq.1), which is less dependent on ambient temperature. Additionally, the duct face velocity and temperature around luminaire needs to have less fluctuation, in order to minimize the effect on the stability of LED. Dusts accumulated on HVAC-LED due to the integration to HVAC air inlet or outlet can affect the LED thermal conductivity at surface, which is also a point of consideration in real design. Furthermore, in order to validate the empirical calculation on the relation between air velocity and HVAC-LED junction temperature, and the relation between
air velocity and efficacy, a test has been set up. Specific procedure and methods are shown in Part III. The results show good relation between tests and empirical calculation (R² between measured junction temperature and calculated junction temperature is more than 0.98; R² between measured efficacy changes and calculated efficacy changes is more than 0.91).

From the results, it is clear that some building has more savings than another one under same climate and lighting system. These are mainly determined by lighting schedules, initial lighting energy density, HVAC system efficiency and heating and cooling hours. A high energy efficiency building will result in less heating and cooling energy changes from lighting retrofit. Similarly, high energy efficient lighting retrofit from T8 to HVAC-LED also needs to insignificant changes on building heating and cooling energy demand. This is mainly because thermal energy contributed by HVAC-LED is much less than T8. Even for a dedicated ceiling situation, the impacts on heating and cooling energy demand are vital. The dedicated ceiling situation refers to a ceiling concept designed to utilize lighting thermal energy in winter and to extract the energy in summer (see Part IV for detailed information). The savings on total heating and cooling energy demand compare to dedicated ceiling to non-dedicated ceiling is less than 5% on average.

5 Conclusion

An integration scenario of LED and HVAC system has been proposed in order to reduce LED operation temperature and bring down the costs. The reductions of HVAC-LED junction temperature under various HVAC ventilation duct face velocity are calculated using empirical method. Both RGB based and phosphor based LED are studied. The increasing of RGB based HVAC-LED efficacy due to the reduction of junction temperature is calculated. The reduction of lighting power density as a result from HVAC-LED increasing efficacy is calculated for five typical commercial buildings. From building energy demand point of view, the annual lighting electricity demand, heating and cooling energy demands of HVAC-LED are calculated based on confidence factors. In order to investigate the secondary effect of integrated HVAC-LED upon building heating and cooling energy demand, the changes of heating and cooling demand are calculated by replacing T8 lighting with HVAC-LED. The retrofit from T8 lighting to non-integrated LED is also calculated for comparison purpose.

The junction temperature of HVAC-LED has been reduced effectively as ventilation duct face velocity increases. For RGB based LED, this means a great potential to reduce lighting power density, and furthermore annual lighting electricity energy demand. The reduction varies from 6% to 40% comparing to T8 lighting.
system, which depends on type of building functions. As comparison, the reduction of replacing T8 system with non-integrated LED is 5-33%, which is less however insignificant.

The reductions of lighting electric energy affect the amount of lighting thermal energy gain to the conditioned space, which affect HVAC heating and cooling energy. Both HVAC-LED and LED replacements to T8 show savings on cooling energy and penalties on heating energy. In general warm climates save more cooling energy; and cool climates suffer more heating energy penalties. The differences between HVAC-LED and LED do not have large differences. This is because LED is already high efficacy lighting. The differences among building types are dependent on various factors such as building lighting power density, lighting schedule, original heating and cooling load of using T8 system, etc.

In general, the integration of LED and HVAC system shows potential to reduce LED’s operation temperature. For RGB based LED, it will increase its efficacy and in the end will reduce building lighting electricity energy demand. The affect to heating and cooling energy demand is more significant when retrofit from T8 to LED, than retrofit from T8 to HVAC-LED. As lighting becomes more energy efficient, the secondary affect to HVAC heating and cooling energy demand will be minimized.
References

16. DOE, Thermal Management of White LEDs, 2009, Building Technologies Program.


### Appendix A - Calculation of Average Illuminance Level Per Building Function

Table A-0-1 Calculation of average illuminance \([E_{\text{building}}, \text{lux}]\) of building

<table>
<thead>
<tr>
<th>Type of Building</th>
<th>Type of area</th>
<th>% of Floor Area</th>
<th>(E_r) Required [Lux]</th>
<th>(E_w) Weighted [Lux]</th>
<th>(E_{\text{building}}) Calculated [Lux]</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Large Office Building</strong></td>
<td>Core Zone</td>
<td>80%</td>
<td>500</td>
<td>400</td>
<td>420</td>
<td>[27]</td>
</tr>
<tr>
<td></td>
<td>Perimeter zone</td>
<td>20%</td>
<td>100</td>
<td>20</td>
<td></td>
<td>Table 4.E.3</td>
</tr>
<tr>
<td><strong>Restaurant</strong></td>
<td>Kitchen</td>
<td>20%</td>
<td>500</td>
<td>100</td>
<td>300</td>
<td>[27]</td>
</tr>
<tr>
<td></td>
<td>Dinning</td>
<td>80%</td>
<td>250</td>
<td>200</td>
<td></td>
<td>Table 4.C.3</td>
</tr>
<tr>
<td><strong>Supermarket</strong></td>
<td>Sale</td>
<td>74%</td>
<td>300</td>
<td>222</td>
<td></td>
<td>[27]</td>
</tr>
<tr>
<td></td>
<td>Dry storage</td>
<td>14%</td>
<td>100</td>
<td>14</td>
<td></td>
<td>Table 4.F.1</td>
</tr>
<tr>
<td></td>
<td>Bakery</td>
<td>5%</td>
<td>300</td>
<td>15</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Deli</td>
<td>5%</td>
<td>500</td>
<td>25</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Office</td>
<td>2%</td>
<td>500</td>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Secondary School</strong></td>
<td>Workshops (Lab,etc.)</td>
<td>13%</td>
<td>750</td>
<td>97.5</td>
<td></td>
<td>[27]</td>
</tr>
<tr>
<td></td>
<td>Classrooms</td>
<td>60%</td>
<td>400</td>
<td>240</td>
<td></td>
<td>Table 4.I.1</td>
</tr>
<tr>
<td></td>
<td>Gym</td>
<td>13%</td>
<td>300</td>
<td>39</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Auditorium</td>
<td>8%</td>
<td>500</td>
<td>40</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Kitchen</td>
<td>2%</td>
<td>500</td>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dining</td>
<td>4%</td>
<td>200</td>
<td>8</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Large Hotel</strong></td>
<td>Guest Room/Corridors</td>
<td>70%</td>
<td>300</td>
<td>210</td>
<td></td>
<td>[27]</td>
</tr>
<tr>
<td></td>
<td>Conference Room</td>
<td>25%</td>
<td>500</td>
<td>125</td>
<td></td>
<td>Table 4.B.4</td>
</tr>
<tr>
<td></td>
<td>Kitchen/Laundry</td>
<td>5%</td>
<td>500</td>
<td>25</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Sources: building function data: 481 prototypical commercial buildings for 20 urban market areas, 1991[27].
Illuminance requirement by building function: EN 12464-1 light and lighting guideline - lighting for indoor work places[32].

### Appendix B – Heating and Cooling Energy Demand Using Conventional T8 Lighting

Table B-0-1 Heating and cooling energy demand of commercial buildings in different climate types, using T8 lighting. [kwh/m²]

<table>
<thead>
<tr>
<th>Building Function</th>
<th>Supermarket</th>
<th>Restaurant</th>
<th>Large Office</th>
<th>Hotel</th>
<th>School</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Climate</strong></td>
<td>Cooling</td>
<td>Heating</td>
<td>Cooling</td>
<td>Heating</td>
<td>Cooling</td>
</tr>
<tr>
<td>Very Hot</td>
<td>156</td>
<td>8</td>
<td>563</td>
<td>10</td>
<td>325</td>
</tr>
<tr>
<td>Hot</td>
<td>149</td>
<td>79</td>
<td>427</td>
<td>86</td>
<td>241</td>
</tr>
<tr>
<td>Warm</td>
<td>90</td>
<td>122</td>
<td>318</td>
<td>253</td>
<td>146</td>
</tr>
<tr>
<td>Mixed</td>
<td>143</td>
<td>178</td>
<td>143</td>
<td>441</td>
<td>94</td>
</tr>
<tr>
<td>Cool</td>
<td>29</td>
<td>269</td>
<td>110</td>
<td>450</td>
<td>72</td>
</tr>
<tr>
<td>Cold</td>
<td>26</td>
<td>296</td>
<td>55</td>
<td>652</td>
<td>54</td>
</tr>
</tbody>
</table>
II. Impacts of Suspended Ceiling Configuration to the Lighting Thermal Energy Gain to Conditioned Space

Validation of Part I assumption: 100% lighting thermal energy added to cooling load
Impacts of Suspended Ceiling Configuration to the Lighting Thermal Energy Gain to Conditioned Space

Ke Li\textsuperscript{a}, D. Cóstola\textsuperscript{a}, Mohammad Mirsadeghi\textsuperscript{b}, J.L.M. Hensen\textsuperscript{a}, Theo Treurniet\textsuperscript{b}

\textit{(a) Building Physics and Services, Eindhoven University of Technology, the Netherlands}
\textit{(b) Royal Philips Electronics N.V.}

1 Introduction

In part 1, in order to calculate the thermal energy gain from lighting to space cooling demand, an assumption is made that 100\% of the lighting thermal energy will be added to conditioned space; regardless of the configuration of suspended ceiling. In order to study how changing the ceiling configuration will affect the amount of lighting thermal energy gain to conditioned space, a series computer simulations have been set-up to compare various suspended ceiling settings with non-suspended ceiling (plain ceiling) settings. The reason for the comparison is that the thermal energy from lighting from plain ceiling is considered to enter conditioned space 100\%. Integrated Environmental Solution Software (IES/VE) is used for simulation.

2 Methodology

This chapter describes the settings of LED luminaire, plain and suspended ceiling, as well as simulation input of a typical commercial office building. The overall procedure is shown in Figure 2-1.

![Figure 2-1 simulation procedure of validation process](image-url)
### 2.1 Large Office Building Model

Simulation inputs of the large office building model are described in Table 2-1. The properties and schedule of the inputs are according to the DOE commercial building benchmark, as mentioned part 1[1].

#### Table 2-1 Large Office Building input in computer simulation using IES/VE

<table>
<thead>
<tr>
<th>Geometry</th>
<th>Thermal properties</th>
<th>System setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>External wall</td>
<td>Heating set-point</td>
</tr>
<tr>
<td>Philips Lighting Office Building</td>
<td>R-value: 1.43 (m²K/W)</td>
<td>21°C</td>
</tr>
<tr>
<td>Total floor level</td>
<td>Ground contact floor</td>
<td>Cooling set-point</td>
</tr>
<tr>
<td>7 above ground</td>
<td>R-value: 0.54 (m²K/W)</td>
<td>24°C</td>
</tr>
<tr>
<td>Floor height</td>
<td>Schedule</td>
<td></td>
</tr>
<tr>
<td>3.96 (m)</td>
<td>Same as DOE Benchmark</td>
<td></td>
</tr>
<tr>
<td>Ceiling plenum height</td>
<td>Roof</td>
<td></td>
</tr>
<tr>
<td>1.22 (m)</td>
<td>R-value: 2.85 (m²K/W)</td>
<td>No HVAC setting for plenum</td>
</tr>
<tr>
<td>Room space height</td>
<td>Window</td>
<td></td>
</tr>
<tr>
<td>2.74 (m)</td>
<td>U-factor: 3.24 (W/m²K)</td>
<td></td>
</tr>
<tr>
<td>Floor surface area</td>
<td>Suspended ceiling</td>
<td>Type: gypsum plasterboard</td>
</tr>
<tr>
<td>3200 (m²)</td>
<td>R-value: 3.55 (m²K/W)</td>
<td></td>
</tr>
<tr>
<td>Window to wall ratio</td>
<td>Internal ceiling/floor</td>
<td>R-value: 0.44 (m²K/W)</td>
</tr>
<tr>
<td>0.38</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 2-2 shows rendering of the office building in IED/VE.
2.2 Luminaire setting and power conversion

For suspended ceiling, luminaire is recessed on the ceiling, which uses HVAC-LED. The heat sink of the luminaire is in the plenum space, and the optical part is in the conditioned space. The efficacy of the luminaire is same as calculated from Phase 1, which is 120 lm/w for RGB based luminaire under 2.5 m/s flow speed. In IES/VE, thermal energy transferred from luminaire needs to be set up under the ‘internal gain’ section. For suspended ceiling, the internal gain from luminaire is separated by the ceiling; thermal energy goes partially to space and partially to plenum. The total internal gain equals to the lighting power density of luminaire. For plain ceiling, the internal gain is not split and equals to the lighting power density (see part I, Table 3-1 for lighting power density of HVAC-LED).

Additionally, IES/VE also requires input of ‘radiant ratio’ of luminaire. In the case of LED lighting, no infrared radiation is presented, however visible light radiation need to be considered because it is part of electromagnetic radiation which contains energy. According to the definition of lumen, 1 lm of white light contains about 0.003226 W of energy. Thus a 120 lm/w efficacy LED contains 120 [lm] * 0.003226 [w] = 0.39 [w] of energy from visible light; which is 39% of visible light conversion. Furthermore, because recessed LED in ceiling has heat sink at top, the heat gain through convection and conduction will go to plenum through heat sink.

Table 2-2 shows the settings of HVAC-LED in plain ceiling and suspended ceiling.

Table 2-2 Setting for luminaire internal gain in IES/VE

<table>
<thead>
<tr>
<th>Setting</th>
<th>HVAC-LED</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Plain Ceiling</td>
</tr>
<tr>
<td>Efficacy [lm/w]</td>
<td>120</td>
</tr>
<tr>
<td>LPD [w/m²]</td>
<td>4.79</td>
</tr>
<tr>
<td>Energy split to space zone</td>
<td>100%</td>
</tr>
<tr>
<td>Radiant energy ratio to space zone</td>
<td>39%</td>
</tr>
<tr>
<td>Energy to plenum zone</td>
<td>N/A</td>
</tr>
<tr>
<td>Radiant energy ratio to plenum zone</td>
<td>N/A</td>
</tr>
</tbody>
</table>

2.3 Ceiling configurations of height and R-value

Schematic drawing of the plain ceiling and suspended ceiling configurations are shown in Figure 2-3.
Figure 2-3 Plain Ceiling configuration (left) and suspended ceiling configuration (right)

For the plain ceiling configuration, only one thermal zone is modelled. The suspended ceiling configuration includes two thermal zones: space zone and ceiling plenum zone. The plenum zone has no HVAC condition. By comparing the heating and cooling energy demand of these two ceiling set-ups, it is able to indicate how suspended ceiling will affect the thermal gain from lighting. The suspended ceiling has been changed R-value and height (see Table 2-3).

Table 2-3 Variant suspended ceiling setting

<table>
<thead>
<tr>
<th>Plenum Setting</th>
<th>Basic</th>
<th>Change R-value</th>
<th>Reduce Height</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plenum height [m]</td>
<td>1.22</td>
<td>1.22</td>
<td>0.82</td>
</tr>
<tr>
<td>R-value [W/m²•K]</td>
<td>0.28</td>
<td>0.56</td>
<td>0.28</td>
</tr>
</tbody>
</table>

The simulation results of the above ceiling set-ups in large office in six climates are provided in section 3.

3 Results and discussion

This section first shows the simulation results in terms of heating & cooling energy demands of a typical office building in mixed climate region, compare plain ceiling with suspended ceiling results; then the summary results of all six climate regions are shown in table.

The result (Figure 3-1) shows that adding suspended ceiling will reduce total heating and cooling energy by 2.7% compare to equivalent-plain ceiling. This means that the majority of lighting thermal energy is added to HVAC load. The differences on load calculation between assumption and simulation are insignificant.
Figure 3-1 heating and cooling energy demands [kWh/m²] of different suspended ceiling settings in typical office building, compare to plain ceiling settings, in mixed climate.

The reason for the different result is that when adding suspended ceiling, the volume of space zone need to be conditioned is reduced. Increasing R-value or reducing the height of the suspended ceiling has not significant influence on the total heating and cooling energy demand. For all climates, the total heating and cooling energy demands of suspended ceiling are reduced on average by 4% compare to plain ceiling (see Table 3-1).

Table 3-1 Energy demands differences between plain and suspended ceilings

<table>
<thead>
<tr>
<th>Climate</th>
<th>Net Savings [kWh/m²]</th>
<th>Relative Savings [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very hot</td>
<td>-3.4</td>
<td>-4.1%</td>
</tr>
<tr>
<td>Hot</td>
<td>-3.5</td>
<td>-3.9%</td>
</tr>
<tr>
<td>Warm</td>
<td>-1.3</td>
<td>-4.8%</td>
</tr>
<tr>
<td>Mixed</td>
<td>-1.1</td>
<td>-2.7%</td>
</tr>
<tr>
<td>Cool</td>
<td>-2.4</td>
<td>-4.2%</td>
</tr>
<tr>
<td>Very cold</td>
<td>-3.2</td>
<td>-4.9%</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>-2.5</strong></td>
<td><strong>-4.1%</strong></td>
</tr>
</tbody>
</table>

This result shows that in general the heating and cooling energy demands of using plain ceiling and suspended ceiling do not differ much. The Part I assumption that all lighting thermal energy will be added to HVAC load is still valid.

4 Conclusion

The Part II intends to investigate how changing suspended ceiling settings will affect the amount of lighting thermal energy being conditioned by HVAC system. Typical commercial building model with plain ceiling
setting and various suspended ceiling setting is built up in computer simulation software IES/VE. Six climate types are considered. The results show insignificant differences between heating and cooling energy demands among different ceiling configurations. The differences are caused by the changing space volume of conditioned zone, by adding up suspended ceiling. Climate types have little influence on the ceiling configuration either. In general, the assumption from Part I that 100\% of lighting thermal energy will be added to conditioned space is considered vali

d.

Reference

III. Experiment: Relation between Duct Face Velocity and HVAC-LED Junction Temperature and Efficacy

Validation of empirical calculation results from Part I
Experiment on the Relation between Duct Face Velocity and HVAC-LED Junction Temperature and Efficacy Change—Validation of Empirical Calculation Result from Part I

Ke Li\textsuperscript{a}, D. Cóstola\textsuperscript{a}, Mohammad Mirsadeghi\textsuperscript{b}, J.L.M. Hensen\textsuperscript{a}, Theo Treurniet\textsuperscript{b}

\textit{(a) Building Physics and Services, Eindhoven University of Technology, the Netherlands}

\textit{(b) Royal Philips Electronics N.V.}

1 Introduction

When integrate LED luminaire with ventilation air duct, the forced convective airflow will remove heat generated from LED. One consequence is a reduction of junction temperature, which eventually increases the lumious flux output. RGB based LED shows more significant improvement than phospher based LED. For a room that has a fixed illuminiance requirement, the increasing lumious flux of LED will require less number of LED needs to be installed, thus result in energy saving (see Figure 1-1). In part I, the decreases of HVAC-LED junction temeprature and the increases of efficacy are calculated using empirical method. The tubular LED under air flow is modeled as long cylender in external vertical forced flow (see Part I, Eq. 1-5). Since the calculation results lead to high lihgting energy saving potential, it is crutial to validate the calculation. This part intents to validate the relation between changing air velocity and HVAC-LED junction temperature; and the relation between changing air velocity and HVAC-LED relative lumen output, as calculated in Part I. The changes in relative lumen output share the same trends of the changes in HVAC-LED efficacy. The changes in relative lumen output is the changes in percentage in comparison to the LED initial lumen output (100%).

![Diagram]

\textit{Figure 1-1 Purpose of conducting the experiment}
2 Methodology

2.1 Experiment Procedure

Figure 2-1 shows the procedure of the experiment.

Step 1: All equipment and luminaires need to be set in a large free convection box to prevent external flow disturbance, the specific set-up method and equipment used are shown in section 2.2.

Step 2: Switch on LEDs and stabilize them for 10 minutes.

Step 3: Measure LEDs surface temperature to provide a reference value under free convection condition.

Step 4: Turn on the fan and increase fan speed until the reading reach 0.3 m/s. Stabilize again the LED for 10 minutes, then record the junction temperature and average illuminance level on the bottom of the free convection box.

Step 5: Slowly increase fan speed, and repeat step 3. Measure when the air velocity increment reaches every 0.3 m/s. Continue step 5 until the fan speed reaches its maximum value.

Step 6: Finish experiment, calculate LED junction temperature by the surface temperature measured. Plot on chart the relation between air velocity and LED junction temperature; as well as the relation between air velocity and LED relative lumen output.

Step 7. Adjust empirical calculation model input (LED length, diameter, electric power) to the testing LED, compare the new empirical calculation results with experimental results.

2.2 Initial set-up and equipment

Figure 2-2 shows the initial set-up inside a black surface free convection box. A round section air duct is fixed in vertical direction. A 12v DV fan is fixed into the duct; sponge is used to prevent vibration. A mesh layer is placed under the fan, which is used to regulate uniform flow. Two 24V DC LEDs (Figure 2-4) are hung right below the duct. On the center back surface of the LED, K-type thermal couples are attached. Because the back
surface is aluminum, aluminum tape is used to minimize the error of changing surface conductivity (Figure 2-3).

A hotwire velocity meter is set near to the duct; the needle with sensor on it is fixed parallel with the direction of the two LEDs, in the center. The ‘flow direction’ arrow mark on the handle of velocity meter is turned to be the same direction of fan flow.

Figure 2-2 Initial set-up of experiment inside a black free convection box

Figure 2-3 Thermal couples are attached on the back center surface of LED, using aluminum type.
Figure 2-4 Testing LED luminaire Philips InteGrade 144 mm long

The instruments and equipment used in the experiment is shown in Table 2-1.

Table 2-1 List of experiment instruments and equipment

<table>
<thead>
<tr>
<th>Equipment/Instrument</th>
<th>Producer</th>
<th>Type</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 LED Luminaire</td>
<td>Philips</td>
<td>InteGrade 144 mm length</td>
<td>Mixed RGB based and Red LEDs</td>
</tr>
<tr>
<td>DC Fan</td>
<td>AVC</td>
<td>Hydraulic Bearing Fan</td>
<td>12V DC</td>
</tr>
<tr>
<td>Thermocouple</td>
<td></td>
<td>K-Type</td>
<td>For both ambient temperature and LED surface temperature measurement</td>
</tr>
<tr>
<td>Lux Meter</td>
<td>Meterman</td>
<td>LM631</td>
<td></td>
</tr>
<tr>
<td>Hotwire Velocity Meter</td>
<td>TSI</td>
<td>s-752 sensor 8910 power supply</td>
<td></td>
</tr>
</tbody>
</table>

2.3 Adjustment on empirical calculation model

Due to the constraint of finding RGB based 4 feet (1200 mm) length white LED, the experiment used 144 mm long white LED luminaire which is composed of RGB and Red LED components. Therefore the empirical calculation model needs to be adjusted accordingly to the experiment luminaire’s dimension and power input.

<table>
<thead>
<tr>
<th>Critical input</th>
<th>Value before adjustment (HVAC-LED in Part I)</th>
<th>Value after adjustment (Philips InteGrad LED)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient temperature [°C]</td>
<td>30</td>
<td>25</td>
</tr>
<tr>
<td>Input power [W]</td>
<td>18</td>
<td>2</td>
</tr>
<tr>
<td>Length [mm]</td>
<td>1200</td>
<td>144</td>
</tr>
<tr>
<td>Surface area LED [m²]</td>
<td>0.096</td>
<td>0.009</td>
</tr>
<tr>
<td>LED thermal conductivity [KW]</td>
<td>3</td>
<td>0.5</td>
</tr>
</tbody>
</table>

When under free convection flow, the empirical equation in Part I cannot be used. The Nusselt number is therefore calculated based on external free convection equation (Eq.1).

\[
Nu_L = \left( 0.825 + \frac{0.387Ra^{1/6}}{[1 + (0.492/Pr)^{9/16}]^{6/27}} \right)^2
\]  

Eq. 1
Nu\textsubscript{L} is the average Nusselt number of vertical cylinder in external free convection. Ra is Rayleigh number and Pr is Prandtl number.

3 Results and Discussion

Figure 3-1 shows the relation between junction temperature and air velocity for both measured and calculated results. Both of the measured and calculated results show good correlation ($R^2 > 0.98$). The measured value on average is lower than the calculated value, this can be caused by the fact that the testing LED is not in a regular cylinder shape, which results in a larger surface area. Figure 3-2 shows the relation between the relative lumen output (in %) and air velocity, for both measured and calculated value. The $R^2$ between the two lines are more than 0.91, which shows also good relation. The measured values are plotted in a curve line, and the calculated values are in a straight line. This is because the calculated LED is only considered composed of RGB based LEDs; but the measured LED has both Red and RGB based LEDs inside. The sensitivity of red LED is slightly higher than the sensitivity of RGB to temperature.

![Figure 3-1: Junction temperature and air velocity relation, between measured and calculated value](image-url)
100% relative lumen output is the initial lumen output of LED under free convection.

4 Conclusion

Part III intends to validate the empirical calculation results on the relation between air velocity and LED junction temperature, as well as the LED efficacy. An experiment has been set-up to validate the calculation. The surface temperatures of two LED under an air duct with increasing air velocity are measured; the average illuminances of the LEDs are recorded. As results, the measured and calculated values show good correlation with each other.
IV. Dedicated Ceiling Concept and Simulation
Dedicated Ceiling Concept and Simulation

Ke Li\textsuperscript{a}, D. Cóstola\textsuperscript{a}, Mohammad Mirsadeghi\textsuperscript{b}, J.L.M. Hensen\textsuperscript{a}, Theo Treurniet\textsuperscript{b}

\textsuperscript{(a) Building Physics and Services, Eindhoven University of Technology, the Netherlands}
\textsuperscript{(b) Royal Philips Electronics N.V.}

1 Introduction

The dedicated ceiling concept refers to the ceiling which is able to utilize thermal energy from HVAC-LED during winter, and extract the energy during summer, for energy saving purpose. This part intends to examine the energy saving potential of applying such concept via a set of computer simulations.

2 Methodology

2.1 Simulation procedure

The overall simulation procedure of dedicated ceiling concept is shown in Figure 2-1. The dedicated ceiling is a ceiling concept which is able to use return air flow pick up thermal energy of luminaire: the amount of thermal energy is rejected to outdoor in cooling season; and reused in the space zone in heating season.

![Figure 2-1 Overview simulation procedure of dedicated ceiling](image)

The simulation procedures include six climates. The setting of large office building from part 1 is continuously used here. Two types of ceilings are set up: dedicated ceiling, which use integrated HVAC-LED luminaire; and non-dedicated ceiling (or normal suspended ceiling) which use either T8 luminaire or HVAC-
LED. The simulations of using T8, HVAC-LED in non-dedicated ceilings are references in order to compare the energy saving potentials. Computer simulation software IES/VE is used in this Part.

2.2 Dedicated ceiling set-up

Figure 2-2 left shows the settings of the dedicated ceiling in cooling season. Return air flow will cool down LED luminaire by picking up its non-radiation thermal energy. Air circulation in the ceiling plenum will reject the heat outdoor to reduce cooling energy demand.

![Diagram of dedicated ceiling in cooling season](image)

**Figure 2-2 Dedicated ceiling in cooling season (left) and heating season (right).**

Figure 2-2 (right) shows the dedicated ceiling operation in heating season. The plenum will stop rejecting return air outdoor; instead, the return air will be directed to ventilation shaft and mix with supply air. Meanwhile the air flow speed cross luminaire is still maintained in order to cool down the LED. In order to compare with dedicated ceiling, non-dedicated ceiling is used as reference. Figure 2-3 shows the configuration of non-dedicated ceiling with T8 luminaire. There will be no air flow around T8 to cool it down; and no heat extraction of the luminaire. The internal gain setting of T8 in IES/VE is shown in Table 2-1.
Figure 2-3 Non-dedicated ceiling

Table 2-1 Setting for T8 internal gain

To achieve the dedicated ceiling in IES/VE, the settings of internal gain from lighting in the ceiling plenum is set to be 0 [W/m²] during cooling season. The settings of internal gain in heating season remain the same as non-dedicated ceiling, as shown in Table 2-2 for HVAC-LED and Table 2-1 for T8.

Practical detailed design has not been included in this Phase. Other simulation configurations

3 Results and Discussion

The results of heating, cooling and lighting energy demands are shown in Figure 3-1, for large office building in mixed climate.
Figure 3-1 Energy demand of dedicated ceiling compare to non-dedicated ceiling in mixed climate.

Comparing the between the same non-dedicated ceiling, using the HVAC-LED luminaire will save 21.2% heating, cooling and lighting energy demands than using T8 luminaire. Both of the cooling and lighting energy demands are reduced, the heating energy demand is increased. This is because the HVAC-LED power density is much less (52.7%) than T8. The lighting thermal energy from HVAC-LED added to HVAC load is also less than from T8. Accordingly, the lighting thermal energy from HVAC-LED can be used for heating becomes less. Comparing energy demands between the dedicated ceiling and non-dedicated ceiling configurations, for same HVAC-LED, the dedicated ceiling set-up can save 3.7% in total. This saving is a solo contribution from savings from cooling energy.

Table 3-1 shows the total energy demands of three simulation set-ups: T8 without HVAC integration, in non-dedicated ceiling; HVAC-LED cooled with return air, in non-dedicated ceiling and the same HVAC-LED, in dedicated ceiling.

**Table 3-1 Total energy demands of three simulation settings**

<table>
<thead>
<tr>
<th>Climate</th>
<th>T8 non-dedicated ceiling [kwh/m²]</th>
<th>HVAC-LED with return air</th>
<th>Non-dedicated ceiling [kwh/m²]</th>
<th>HVAC-LED with return air Dedicated ceiling [kwh/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very hot</td>
<td>123.8</td>
<td>101.1</td>
<td>96.0</td>
<td></td>
</tr>
<tr>
<td>Hot</td>
<td>128.3</td>
<td>106.2</td>
<td>101.7</td>
<td></td>
</tr>
<tr>
<td>Warm</td>
<td>66.7</td>
<td>45.6</td>
<td>43.4</td>
<td></td>
</tr>
<tr>
<td>Mixed</td>
<td>74.1</td>
<td>60.3</td>
<td>58.1</td>
<td></td>
</tr>
<tr>
<td>Cool</td>
<td>91.1</td>
<td>76.9</td>
<td>74.6</td>
<td></td>
</tr>
<tr>
<td>Very cold</td>
<td>96.9</td>
<td>83.1</td>
<td>80.8</td>
<td></td>
</tr>
</tbody>
</table>

Energy demands savings if using dedicated ceiling in terms of percentage are shown in Figure 3-2, compare with T8 in non-dedicated ceiling; Figure 3-3 shows the comparison to HVAC-LED in non-dedicated ceiling.
In general, the energy demand savings have higher potential in warmer climates, comparing to cooler climates. This is because the dedicate ceiling mainly contribute to cooling energy demand reduction. The cooling energy demand of warmer climates is higher than of cooler climates generally.

The highest energy saving occurs at warm climate. This is because the heating and cooling energy demand is not high originally.

Figure 3-3 Energy saving in % compare HVAC-LED in dedicated ceiling and HVAC-LED in non-dedicated ceiling

The saving potential when compare the same HVAC-LED luminaire under different ceiling types show vital savings. This also means the dedicated ceiling has not much improvement on energy saving, because the HVAC-LED is already very high energy efficient lighting.
4 Conclusion
The concept of dedicated ceiling does not show a large advantage than non-dedicated ceiling in the treatment of integrated HVAC-LED, which is because the HVAC-LED has lower thermal energy to be used.