A LABORATORY METHOD FOR MEASURING THE HEAT DISTRIBUTION OF LUMINAIRES AND ITS APPLICATION FOR BUILDING HEATING AND COOLING ENERGY SAVING

BY

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ABSTRACT

This study was aimed to explore the energy saving potential of a new system architecture of solid-state lighting fixtures that was designed to help utilize the heat generated by LEDs for spacing heating in heating season and re-heating in cooling season. The new system architecture, which deploys an innovation of integrative light and heat arrangement in low profile, helps harvest the LED heat and direct most of the heat to the room space while minimizing heat leakage to the ceiling cavity. A well-designed laboratory experiment was carried out in a newly developed Calorimeter chamber that was used to find out heat distribution of luminaires in the conditioned room cavity and ceiling plenum, followed by an estimation of potential energy savings via computer simulation in Energy Plus. A typical primary elementary school classroom was used in this computer simulation equipped with LED fixtures with different heat distribution patterns. It was found that in heating season, the building space heating energy consumption could be reduced as the 'conditioned space/ceiling plenum split' increased. While in cooling season, the LED heat gain in the conditioned room could be utilized to warm up the chilled supply air to supplement the function of reheating system. The new system architecture of LED fixtures with integrative lighting and heating arrangement could save 4.4%-4.7% of annual building heating and cooling energy uses by reducing reheating energy consumption in cooling season and space heating energy consumption in heating season.

ACKNOWLEDGMENTS

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CHAPTER 1

INTRODUCTION

1.1 Background

1.1.1 Thermal Performance of LED luminaires

Light-Emitted Diode (LED) lighting is a relatively mature technology today in current lighting industry, which could provide the same amount of lumen output with much less energy consumption (compared to conventional light sources). LED luminaires are considered energy efficient and economical products because of their long life.

On the other hand, LED lighting has underestimated by-product of heat generation. When LED generates light, 20%-30% of its electrical energy consumptions will be emitted as visible light, and the rest 70%-80% of its consumed energy will be converted to heat (U.S Department of Energy, 2008). Electroluminescence is the process in which LED chips generate light and heat (Figure 1). In ideal electroluminescence process, when an electron meets a hole, it falls into a lower energy level and releases energy by generating a photon. Yet in most cases, electrons fallen into lower energy level will generate heat instead of emitting photons. This heat will stay in the diode and cause temperature raising up quickly at the back of the LED chips.

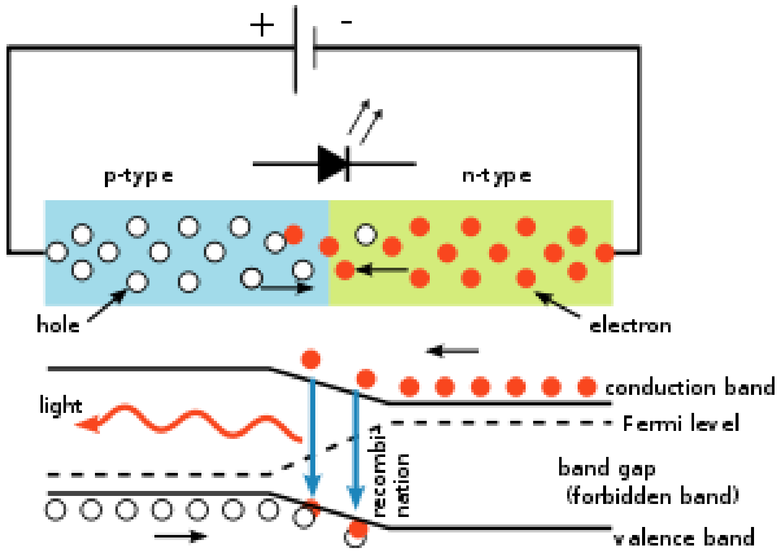


Figure 1 Ideal electroluminescence process generating photons in the PN-Junction of solid-state lighting fixture (S-Kei, 2011)

To prevent LED chips from being burned out with overheat, a thermal heatsink is mounted on the back of LED to haul the heat stored on the back of LED chips away to cool the LED junction. The heatsink is made of materials with high thermal conductivity (e.g. Aluminum, 118 Btu/hr °F ft) and often designed with a large surface area (e.g., with fins) to quickly dissipate heat to ambient environment through convection with ambient air. Because most of the heat is generated on the back of LED that is quickly removed using heatsink, the temperature of the front surface of an LED light source is often only slightly higher than the ambient temperature. The highest operating temperature of LED chips is regulated as 120 °C (248 °F) in current industrial standard (Hui, 2017).

Compared to conventional light sources, LEDs have two unique advantages that may change the lighting practice. First, conventional light sources such as incandescent bulbs or fluorescent tubes are with large size, often too big to be installed in small spaces of built structures or to be integrated with building heating, ventilation and air conditioning (HVAC) systems. In contrast, LED chips are tiny, can be installed in small spaces in low profile to enable innovative LED luminaires of next generation that integrate well with building systems. Second, the significant amount of heat generated by LED chips are accumulated and stored on the back of the LED, not radiated together with the light emitted in the forward direction, which is different from conventional light sources that generate light and heat in a mixed energy flux in the same direction. As a result, the heat generated by LED light source can be easily controlled and harvested without interfere its lighting performance (Cai, 2015).

Because of the two unique characteristics, a new luminaire system architecture of "Heat Arrangement of LED Arrays in Low Profile" was developed by Cai (Cai, 2017, "Integrated Light and Heat Arrangement of Low-Profile Light Emitting Diode Fixture". Non-provisional application No. 15/486,797, publication No. US-2017-0299167-A1) for integrative light and heat arrangement in low profile, as shown in Figure 2, from which future solid-state lighting fixtures could benefit. Via the new architecture of "Heat Arrangement of LED Arrays in Low Profile", the heat generated by LEDs can be effectively harvested and quickly dissipated into conditioned interior space for beneficial heating uses, without interruption of the LED light output. For example, LEDs in an array can be mounted on passive heat exchanger and integrated with lens in the front side and a layer of insulation materials on the back for making integrative LED fixtures in low profile (Figure 2). Such slim LED fixtures can be ceiling recessed, surface mounted, or hung from the ceiling for integrative heating and lighting in conditioned interior spaces. Additionally, LEDs can be attached to the metal frame of traditional supply air diffuser to make a light and heat integrated air diffuser (Figure 3). It is thus expected that LED luminaires of next generation might be re-designed and re-engineered to integrate with the building HVAC system and maximize building energy savings in space heating, cooling, and lighting.

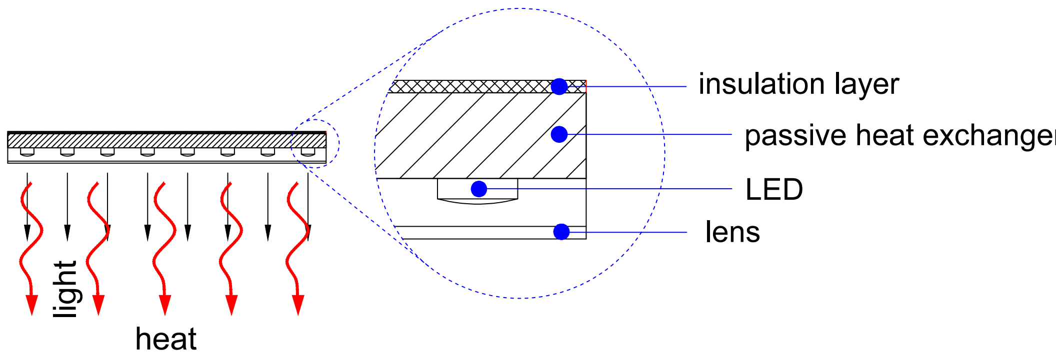


Figure 2 A new luminaire system architecture of "Heat Arrangement of LED Arrays in Low Profile" to harvest both the light and the heat generated by the same LEDs via a mingled path for lighting and heating uses (Cai, 2017).

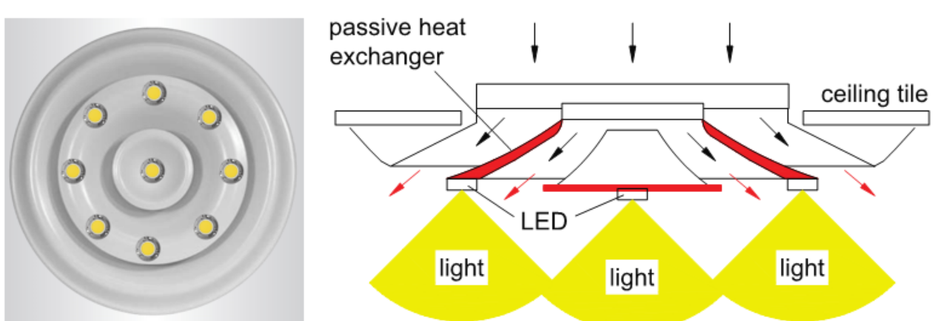


Figure 3 Heated air diffuser with LED lights (Cai, 2015)

In fact, the impact of conventional lighting on building heating and cooling energy consumption has been well studied. Previous study (Fisher & Chantrasrisalai, 2007) on the impact of lighting on the building heating and cooling loads were focused on the integration of ceiling recessed lighting fixtures with air diffuser at the air return side. However, previous studies did not include newer LED lighting technologies, which are quite different from conventional lighting technologies in terms of size, light and heat generation, and real-time working performance. In addition to two unique characteristics of LED fixtures, there are other factors affecting the harvesting of light heat. For example, the ambient temperature affects the performance of fluorescent lights (e.g. Fluorescent T8, T12 lamps) which are designed to give maximum lights output at 25°C (77°F). As a result, conventional fluorescent lamps would be dimmed in a cold ambient environment (e.g., 16 °C at the supply air duct). However, LEDs do not have this problem, because LEDs work more efficiently in a cold environment due to LED heat being quickly removed to lower its junction temperature.

The present study was aimed to evaluate the thermal performance of custom-designed LED luminaires that deploy the new system architecture of “Heat Arrangement of LED Arrays in Low Profile” (Figure 2) in comparison to that of current LED fixtures available in the existing market. To that end, a portable calorimeter chamber (Figure 4) was designed by Dr. Hongyi Cai and constructed by Simon Diederich in the University of Kansas Lighting Research Laboratory in a prior study (Diederich, 2017). The calorimeter was designed for accurate heat transfer measurement of new LED products in well-controlled environments for testing integrated solid-state lighting and heating technologies of next generation. It has a size of approximately 2.6 ft wide, 6.5 ft long, and 6 ft high, divided into a ceiling space and a room space. The U value for the calorimeter walls is preset as 0.32 W/(m2 K) or less. In the present study, the calorimeter was used to measure thermal features (e.g., heating power and the heat distribution patterns) of selected testing LED fixtures, including (i) prototypes of new surface-mounted or ceiling-recessed LED luminaires (Figure 5) that deploy the new system architecture of “Heat Arrangement of LED Arrays in Low Profile” (test case), and (ii) two off-the-shelf commercial LED luminaires which were tested in the calorimeter under the same testing conditions for comparison (control cases).

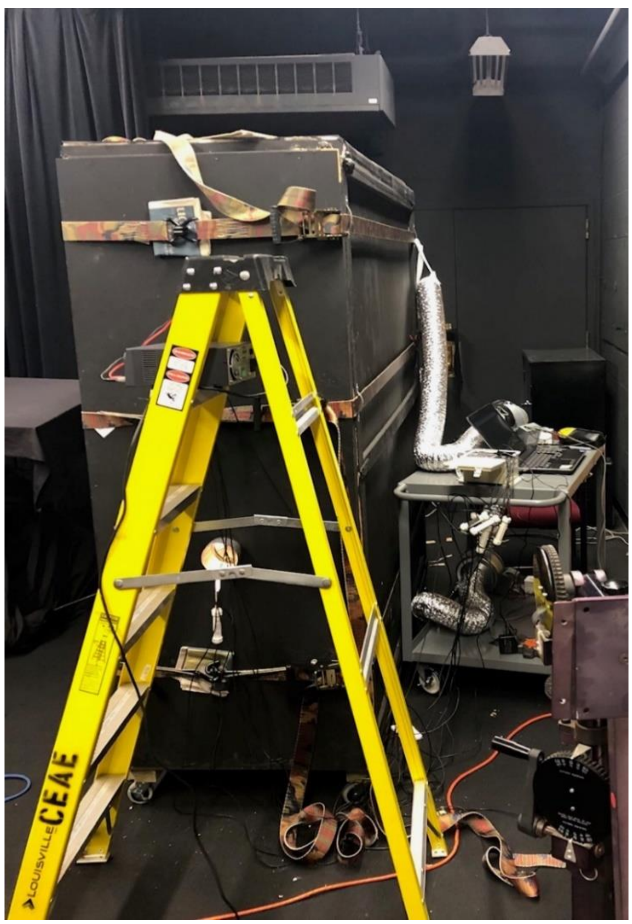


Figure 4 The Calorimeter in the darkroom of KU lighting research laboratory

Figure 5 A prototype ceiling recessed LED fixture that deploy the new system architecture of "Heat Arrangement of LED Arrays in Low Profile"

1.1.2 Energy Plus Simulation

Energy Plus is a building energy simulation software used by engineers, architects, and researchers to simulate annual or seasonal energy consumptions for heating, cooling, ventilation, and lighting in buildings (energyplus.net, 2018). Energy Plus has some notable capabilities in building energy consumption simulation. The load categories and the HVAC system in each conditioned space can be set up and modified, enabling basic needs of the proposed computer-aided simulation in the present study to figure out how much heating and cooling energy may be saved by the new LED fixtures with new system architecture of "Heat Arrangement of LED Arrays in Low Profile".

One key feature of the new LED luminaires (Figure 5) designed and developed in house is that they can harvest and dissipate more LED heat, which is otherwise trapped in the ceiling plenum, into the conditioned room space than current commercial LED luminaires do. During the heating season, the LED heat harvested in the room space is considered a supplemental heating power in Energy Plus simulation. In the cooling season, the air first chilled for moisture control (with air temperature below dew point) needs to be reheated by the re-heating coil of the HVAC system to a satisfying temperature (e.g., above 55°F) before the air is discharged into the room space. The LED heat harvested in the room space from those new LED luminaires is considered supplemental re-heating power, which may help re-heat the discharged air and thus lower the energy consumption of the re-heating coil of the HVAC system (Cai, 2015).

The computer simulation in the present study used a model of a typical classroom (28’×36’) in primary schools built by *Sketch-up Make* (Figure 6), with lighting configurations, climate data and other thermal parameters defined in Open studio (Figure 7). The model was then imported into Energy Plus for simulation of annual building energy consumption. Example simulation results are shown in Figure 8. The cooling and heating energy consumption data were extracted from the Energy Plus simulation report for further data analysis.

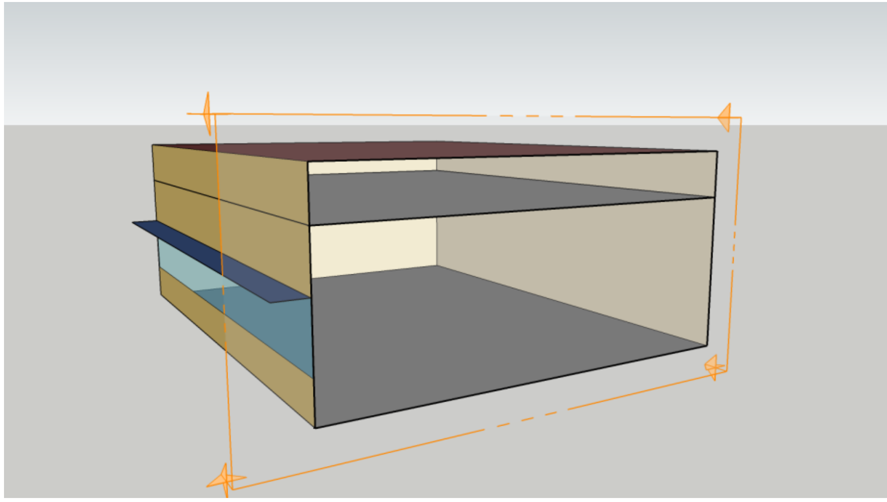


Figure 6 The modeling of the primary school classroom in Sketch Up make

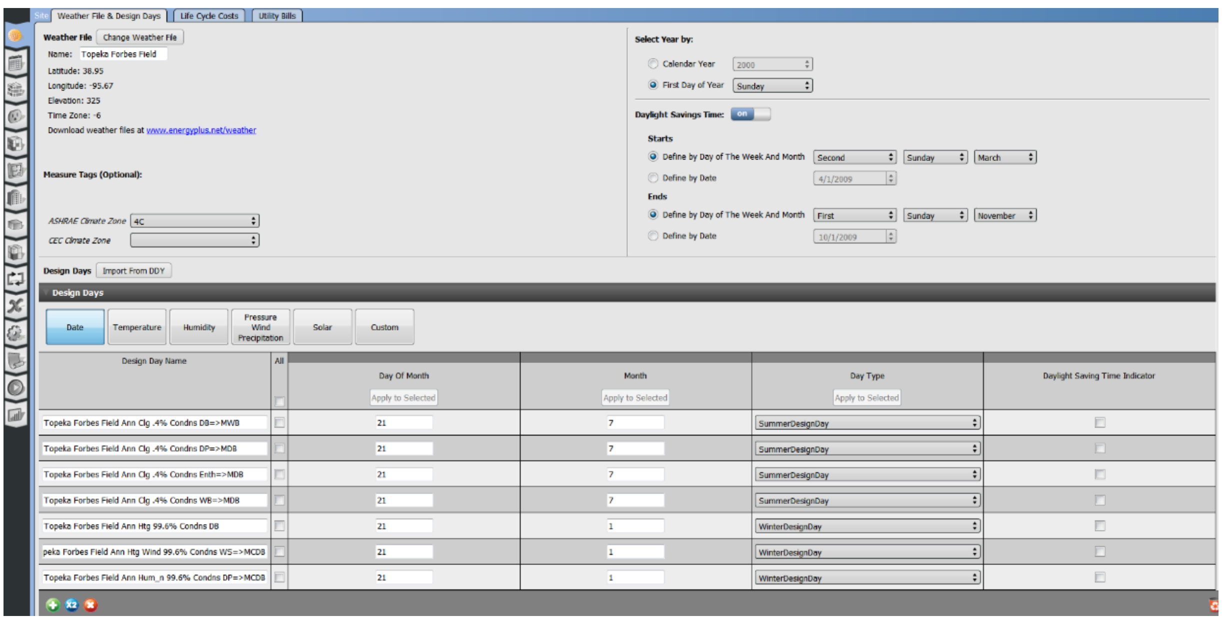


Figure 7 Definition and modification of the modeling in Open Studio

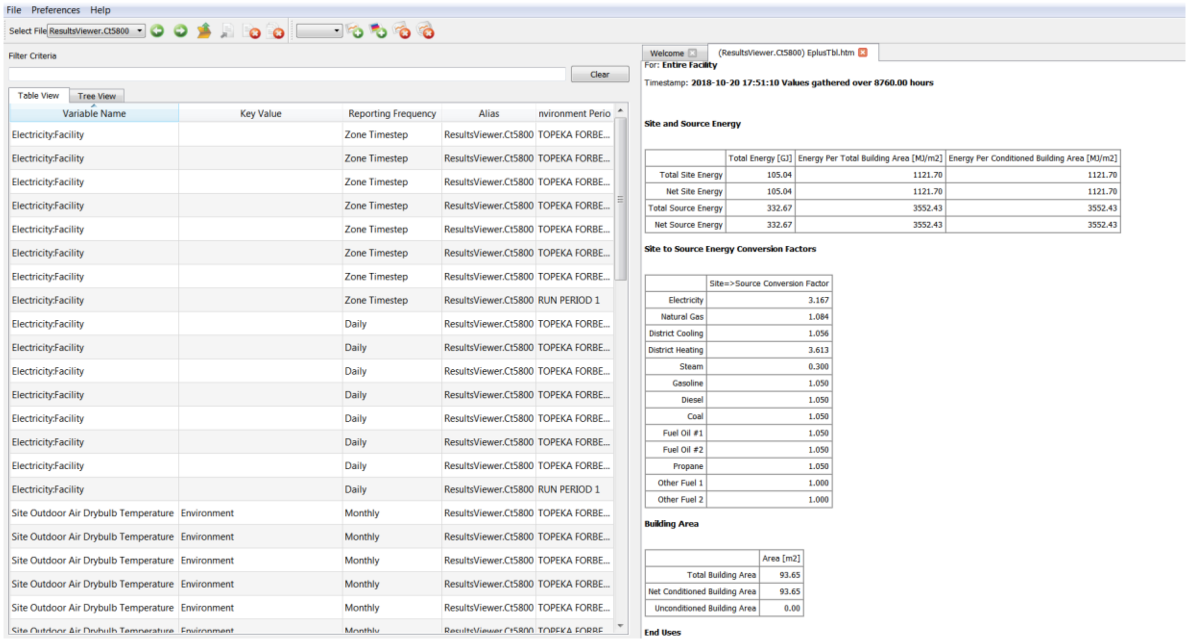


Figure 8 An example of Energy Plus simulation results

1.1.3 Research Problems

There are two major research problems to solve in the present study, as follows:

1) **Research problem #1**: the heat distribution of the new self-designed, custom-made prototype LED luminaires, which adopt the new system architecture of "Heat Arrangement of LED Arrays in Low Profile", is unknown and not yet specified in any existing codes;

2) **Research problem #2**: the heat distribution pattern, as a desired thermal parameter of the prototype LED fixtures, cannot be directly input into Energy Plus for the annual heating and cooling energy simulation in that Energy Plus is incapable of simulation of new LED technologies not yet available in the program's library which has a list of off-the-shelf products available in the market.

To solve the first research problem (*the heat distribution pattern of the new LED luminaires is unknown and not yet specified in the existing codes*), a portable calorimeter was designed and constructed in house (Diederich, 2017) to measure the heat distribution patterns of common lighting fixtures, including those LED luminaires used in the present study. The second research problem (*Energy Plus is incapable of simulation of new LED technologies not yet available in the program's library*) could be solved via numerical approximation in Energy Plus by assigning two separate "heat sources" in the room space and ceiling plenum of the model classroom, respectively, coordinated with target lighting schedule of the specified building space. In Energy Plus simulation, such a "heat source" is only an approximation of the thermal characteristics of the tested LED luminaires without considering the visible light fraction. As a result, in the present study, lighting power of a LED luminaire will be ignored and the nominal power of the tested LED luminaires consists only "heating power" of a luminaire, used for thermal related simulation in Energy Plus via numerical approximation.

1.2 Research Goal and Objectives

The goal of the present study was to validate the energy-saving design of new LED fixtures that deploy the new system architecture of "Heat Arrangement of LED Arrays in Low Profile" to harvest the otherwise wasted heat generated by the same LEDs for an overall reduction in building energy consumptions for heating and cooling.

To that end, a laboratory method was developed to measure a desired thermal parameter of the LED luminaire: the 'conditioned space/ceiling plenum split'. The 'conditioned space/ceiling plenum split' of the heat generated by each LED luminaire is defined as the fraction of the lighting power converted to the lighting heat gain of the conditioned space and the fraction of the lighting power converted to the ceiling plenum's lighting heat gain. Values of the 'conditioned space/ceiling plenum split' were obtained by testing each LED luminaire in the calorimeter under various testing conditions. Results were then used for estimation of annual energy consumptions in follow-up computer simulations in Energy Plus.

Next, a computer model of a primary school classroom (28'×36') was built in which the new LED luminaires were installed for energy simulations in Energy Plus. The heat distribution pattern of each LED luminaire was approximated in Energy Plus in light of those laboratory values of 'conditioned space/ceiling plenum split'. Energy Plus simulation was conducted to estimate how much annual cooling and heating energy can be saved by the new type of LED luminaires that deploy the new system architecture of "Heat Arrangement of LED Arrays in Low Profile". Simulation results obtained in test case of modeling equipped with the new LED luminaires were compared to those obtained in control cases of modeling equipped with off-the-shelf commercial LED luminaires.

In order to achieve the goal, there were three objectives to accomplish in the present study, as follows:

(1) Conduct a pilot study using experiments carried out in the calorimeter put in the Dark Room (1152 Learned Hall) of the University of Kansas Lighting Research Laboratory to explore some key information of the calorimeter and the thermal experiments in preparation for formal experiments.

(2) Conduct formal experiments using the calorimeter put in the Cold Room (G445A M2SEC building) of the Engineering complex, which is a well-controlled interior space with preset constant air temperature and relative humidity, which are adjustable, to explore the thermal performances (e.g., heating power and heat distribution pattern) of the new LED luminaires under different test conditions in comparison to those of selected commercial LED luminaires.

(3) Conduct Energy Plus simulation to calculate annual heating and cooling energy consumptions of the modeled primary school classroom installed with different LED luminaires previously tested in the Cold Room. Additionally, the energy-saving modeling built in Energy Plus was used to find out how much energy can be saved by utilizing the portion of LED heat harvested in the room space as a supplemental reheat source in cooling season.

According to the two unique properties of LED chips aforementioned in chapter 1.1, LED luminaires have heat distribution that is more easily controllable than other types of obsolete luminaires (e.g., fluorescent, HID luminaires). The new system architecture of "Heat Arrangement of LED Arrays in Low Profile" was used in the present study to harvest the majority of heat generated by the LED chips and dissipate the LED heat into the room space while minimizing the heat flow toward the back of luminaires that would be trapped in the ceiling plenum. Figure 9 shows the concept of integrative illumination and HVAC system, in which the harvested LED heat is dissipated into the conditioned space to interact with the HVAC system for overall energy savings. As shown in Figure 9, LED heat is harvested from multiple types of the new LED luminaires, including ceiling mounted, pendant, table top, floor standing fixtures, and LED-integrated air diffusers. The majority of harvested LED heat is directly dissipated into the conditioned room space to reduce space heating loads in winter and the reheating power of HVAC system in summer. To maximize energy saving potentials, ideally all of the LED heat could be harvested in the room space with zero heat trapped in the ceiling plenum so that the heat distribution pattern ('conditioned space/ceiling plenum split') of this new LED technology is 100/0 (100% in room space, 0% in ceiling plenum).

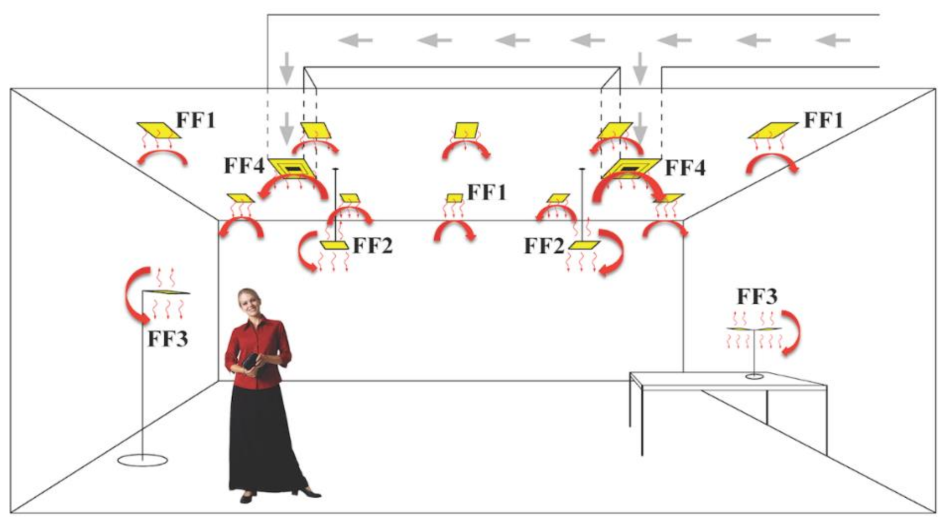


Figure 9 The concept of integrative illumination and HVAC system, in which the harvested LED heat in conditioned space interact with the HVAC system (Cai, 2016)

Using the calorimeter in the Cold Room, this study tested several thermal parameters of the prototype LED luminaire (one prototype with two different mounting methods) with the new system architecture of "Heat Arrangement of LED Arrays in Low Profile" and, for comparison, two off-the-shelf LED fixtures bought from market. The prototype new LED fixtures have nominal power of 54W, as designed, with more heat dissipated down into the room space than going up and trapped in the ceiling plenum. In the Cold Room experiments, the heat generation rate of each type of LED luminaire and its heat distribution pattern ('conditioned space/ceiling plenum split') were calculated using some thermal equations validated in the pilot study.

The final part of the present study was Energy Plus simulation with input from the laboratory tests, including the heating power of each type of LED luminaire and its heat distribution pattern ('conditioned space/ceiling plenum split'). Accordingly, the thermal features in the pre-simulation settings of Energy Plus modeling were defined, and modified later per need, to approximate thermal parameters of LED luminaires obtained in laboratory. In cooling season, the LED heat harvested in the conditioned room space was simulated in Energy Plus as a supplemental reheating source of the HVAC system. It is worth mentioning that during this simulation process, "schedule conflict" was a concern in that the space lighting schedule does not perfectly match the space heating and the cooling schedules. When Energy Plus simulations were done, the percentage of overall building energy saving for space heating and cooling could be estimated by comparing the energy consumption data among different thermal pre-settings related to different types of LED luminaires installed.

CHAPTER 2

LITERATURE REVIEW

2.1 Heat gains from space lighting

Lighting accounts for 10% of total building energy consumption in commercial building in the United States (U.S Energy Information Administration, 2015). Since all electric lights generate heat, which is considered one of the major heat gains of buildings with significant thermal impact on increased building cooling load, if not efficiently removed out of the building. ASHRAE (American Society of Heating, Refrigerating, and Air-conditioning Engineer) recommends a procedure to calculate the cooling load incurred, which uses the 'conditioned space/ceiling plenum split' as an input of heat distribution from luminaires (ASHRAE RP-1282, 2016).

Different types of heat sources generate different proportions of heat. For incandescent lamps, often 80% of input electric power is transferred to thermal radiant, 10% converted to convective and conducted heat, and only 10% transferred to visible light for space lighting (Carrier Air Conditioning Company, 2017);

U.S Department of Energy provide typical heat conversion for "white" light source as shown in Figure 10 (U.S. DoE, Mar 2008). The LED light source have negligible fraction of IR and UV and most of heat (conducted and convected) is dissipated into ambient space. The ceiling plenum/conditioned space split of these 70%-80% conducted and convected heat of LED luminaires that used for this study will be measured by the calorimeter.

ASHRAE also gives some recommended split of sensible heat gain (radiant/convective) from space lighting with different types of light sources such as incandescent, fluorescent, metal halide, and LED. (Engineer Reference, Big Ladder Software LLC, 2018).

Power Conversion for "White" Light Sources				
	Incandescent† (60W	Fluorescent	Metal Halide	LED*
Light	8%	21%	27%	20-30%
IR (radiated)	73%	37%	17%	~0%
UV (radiated)	0%	0%	19%	0%
Total Radiant Energy	81%	58%	63%	20-30%
Heat (Conducted + Convected)	19%	42%	37%	70-80%
Total	100%	100%	100%	100%

* Updated per Multi-Year Program Plan (MYPP) Mar 2008, figure 4-5, pg 58, http://www.netl.doe.gov/ssl/PDFs/SSLMYPP2008_web.pdf.

Figure 10 Heat conversion for typical light sources (U.S.-DoE, 2008)

Heat gain from a lighting fixtures often consists of three fractions: (i) converted heat in the room space, (ii) radiant heat into the room space, and (iii) wasted heat in the ceiling plenum hauled away by zone return air, which is commonly seen in a building equipped with lighting fixtures integrated with return air duct (Figure 11) (Input and Output Reference, 2017, bigladdersoftware.com). Often, three fractions of heat gain from lighting fixtures, including converted and radiant heat in the room space and the trapped heat in the ceiling plenum, are simulated in Energy Plus.

Fisher & Chantrasrisalai (2006) conducted several experiments on heat distributions of overhead fluorescent fixtures, including ceiling mounted and pendant fixtures, in their research “Lighting Heat Gain Distribution in Buildings” (ASHRAE 1282-RP, 2007). Their results are summarized in Table 1. Some kinds of lighting fixtures are designed to attach the return air plenum (as shown in figure 11) or designed to integrated with return air duct. The return air fraction of some lighting fixture is the fraction of heat absorbed by return air.

Not like conventional fluorescent, which may not output 100% lighting power in cold ambient environment, LED lighting fixture can be installed at the supply air side (55°F). Therefore, heat generated by LED fixture might be utilized as part of space heating power and/or part of reheating power. The fraction of heat going down to the room space and going up to ceiling space is named ceiling plenum/room split. The fraction of heat in the room space could be regarded as kind of “supply air fraction” in this study.

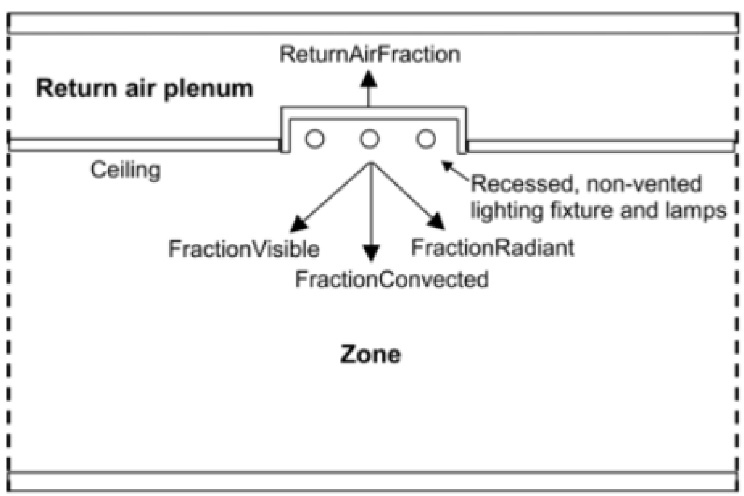


Figure 11 Heat distribution of a fluorescent fixture (bigladdersoftware.com)

Table 1 Fractions of selected overhead fluorescent luminaires (Fisher & Chantrasrisalai, 2007)

Type of Luminaires	Return Air Fraction	Fraction Radiant	Fraction Visible	Fraction Convection
Recessed, Parabolic Louver, Non-Vented, T8	0.31	0.22	0.20	0.27
Recessed, Acrylic Lens, Non-Vented, T8	0.56	0.12	0.20	0.12
Recessed, Parabolic Louver, Vented, T8	0.28	0.19	0.20	0.33
Downlights, Compact Fluorescent, DTT	0.86	0.04	0.10	0.00
Downlights, Incandescent, A21	0.29	0.10	0.6	0.01
Pendant, Indirect, T5HO	0.00	0.32	0.25	0.43
Surface Mounted, T5HO	0.00	0.27	0.23	0.50

Likewise, Rock and Wolf (1997) conducted several computer simulations to find relevance of the heat gain from space lighting with different air supply system. In their study case#2, the air supply and return ducts were equipped in ceiling plenum to haul away possible heat gain from the lighting fixtures by the supply air as it passes through the air ducts. In their simulation results, the supply air temperature maintained at 15°C during the time when HVAC system and lighting system were on (Rock B.& Wolf D., 1997). It was found that the air temperature of the ceiling plenum dropped by about 1.5°C during the time when both HVAC and space lighting system were on.

Ball & Green (1983) created a mathematical model in 1983 to calculate cooling loads from space lighting for a variety of space lighting arrangements. Chung & Loveday (1998) create a thermal model, which consider all heat transfer including conduction, convection and radiation of luminaires to analyze and calculate interior light level, room air temperature and cooling loads (Diederich, 2017). These two studies

Moreover, various methods have been developed to test heat output of luminaires to find its 'radiative/convective split' (the fraction of the lighting heat gain of the conditioned space that is transferred as radiation and the fraction that is transferred as convection) and the 'conditioned space/ceiling plenum split' (the fraction of the lighting power converted to the lighting heat gain of the conditioned space and the fraction of the lighting power converted to the ceiling plenum's lighting heat gain), and new cooling load calculation methods recommend these two splits as input data (AHRAE-RP-1282, 2018). Unfortunately, both 'radiative/convective split' and 'conditioned space/ceiling plenum split' cannot be estimated through simulation in Energy Plus or another software with reliable results, thus, relying on laboratory method (as measured in calorimeter) to figure them out.

2.2 Calorimeter

Calorimeter is one type of instrument commonly used to measure heat of chemical reaction and/or physical change. Mitalas (1973) and his research team of National Research Council of Canada built a full-size room calorimeter to calculate cooling load from space lighting. They designed an air-loop with the same temperature of the insulated wall circulated behind the insulation layers to prevent heat loss. Chantrasrisalai & Fisher (2007) built a room calorimeter in 2007 to calculate cooling load by using air temperature difference between supply and return air. Also, they installed a radiometer to measure 'radiative/convective split' of luminaires. Their research was published in the ASHRAE handbook chapter 18, which indicates how to calculate cooling loads by using heat balance and the radiant time series method (Diederich, 2017).

To calculate the heating power and its ‘conditioned space/ceiling plenum split’ of LED luminaires, Cai and Diedrich designed and built a room calorimeter with simulated ceiling plenum cavity and room cavity in the University of Kansas Lighting Research Laboratory. The theory (Cerbe & Wilhelms, 2011) was used as a reference for the design of the calorimeter as well as output heat power calculation. Two sets of air intake and exhaust systems were installed in the calorimeter in the ceiling plenum and room space, respectively (Diederich, 2017). The room space or ceiling plenum had three temperature sensors to detect real-time air temperature at the air intake, above tested luminaire and at the air exhaust, respectively, as well as one humidity sensor mounted in the middle of the cavity, one fan sensor at air exhaust and one controllable fan to suck air (Diederich, 2017). Air temperature and relative humidity were recorded by HOBO U-30 station data logger, and the air flow rate was recorded by Testo-480 data logger. Based on Cerbe & Wilhelms’s theory, the heating power of LED luminaires was calculated using air temperature difference between the air intake and the air exhaust (measured with temperature sensors) and air-flow rate (measured with fan probes). Next, the heat distribution pattern was calculated by comparing the heating power output from the “room space” and that from the “ceiling plenum” of the calorimeter. This calorimeter was tested and commissioned by Simon Diedrich in his Master thesis study in 2017.

2.3 Reheat system

Reheat system is a component of building air-conditioning system, which can be found in large buildings such as hospital, offices, commercial buildings, etc. The main benefit of reheat system is to control the interior air temperature and humidity at a comfortable level. As shown in Figure 11, returned air from conditioned space will be cooled down to a temperature below dew point to remove moisture (called condensation) for humidity control purpose. The chilled air is then re-heated to a comfortable temperature range by the reheat system before it is discharged into the room space.

The major shortcoming of reheat system is its high energy consumption, which may result in an extra cost for building utilities, especially for a building equipped with the electric coil reheat system. (Madison Gas and Electric Company, 2015).

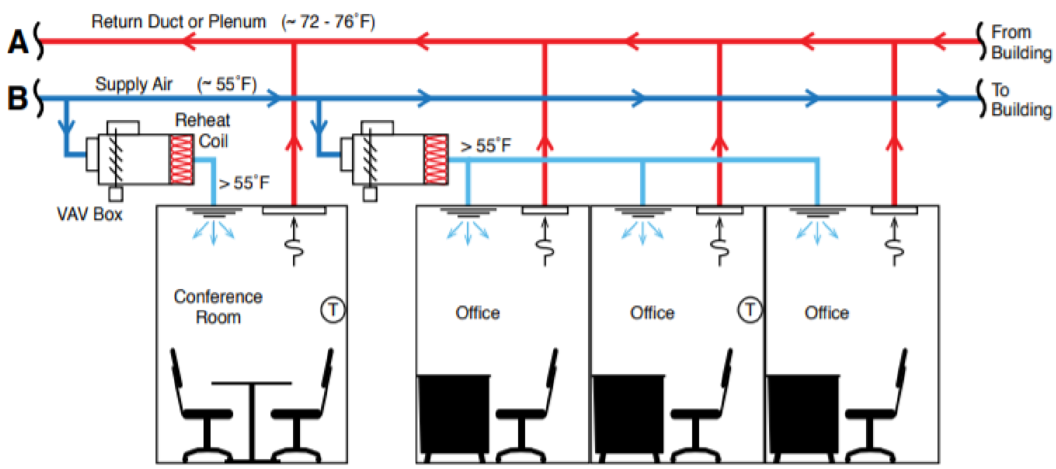


Figure 12 A typical reheat system in commercial building (MGE, 2015)

CHAPTER 3

METHODOLOGY

3.1 Theoretical framework

3.1.1 Calculations

(a) The heating power of tested LED luminaires

Diederich (2017) selected and verified the following calculations process with related equations for data treatment in his thesis, which were used in the present study for covering all mathematical bases for calculating calorimeter output values.

The total output heating power consists of heating output in the ceiling cavity and that in the room cavity, respectively, as shown in Equation (1).

$$\dot{Q}_{total} = \dot{Q}_{ceiling} + \dot{Q}_{room} \tag{1}$$

Where:

$\dot{Q}total$: total heating power of the tested luminaire

$\dot{Q}ceiling$: heating power in the ceiling plenum cavity

$\dot{Q}room$: heating power in the room cavity

For each cavity, the heating power is calculated with the air temperature difference and the mass flow rate using Equation (2).

$$\dot{Q}_{cavity} = (h_{out} - h_{in}) \cdot \dot{m} \tag{2}$$

Where:

$\dot{Q}cavity$: heating power output from room cavity or ceiling cavity

h_{out}: Specific enthalpy of air leaving the calorimeter

h_{in}: Specific enthalpy of air entering the calorimeter

$\dot{m}$: The mass flow rate of air (kg/s)

The specific enthalpy of air is the function of air temperature and absolute humidity at this specific temperature, calculated using Equation (3) (Cerbe & Wilhelms, 2011). In Equation (3), air temperature is measured with temperature sensors in the present study.

$$h = C_{pL} \cdot t + x \cdot (C_{pD} \cdot t + \gamma_D) \tag{3}$$

Where:

C_{pL}: Specific heat capacity of air, 1.004 KJ/kg*K

C_{pD}: Specific heat capacity of steam, 1.86 KJ/kg*K

t: Air temperature (Kelvin)

γ_D: Evaporation heat at 273.15K, 2500KJ/kg

x: Absolute humidity ($kg_{water}/kg_{dry\ air}$)

The absolute humidity is calculated using Equation (4). In Equation (4), water vapor saturation pressure at specified temperature can be calculated using online engineering toolbox (www.engineeringtoolbox.com), and that temperature shall be the laboratory environment air temperature in the present study. Barometric pressure on the test date can be obtained online from *weather.com*.

$$x = 0.622 \cdot \frac{p_{s(t)}}{\frac{p}{\varphi} - p_{s(t)}} \tag{4}$$

Where:

$p_{s(t)}$: Water vapor saturation pressure (kPa)

p: Barometric pressure (kPa)

φ: Relative humidity (range: 0-1)

The mass-flow rate of air can be calculated from air volume-flow rate and the absolute humidity, using Equation (5) (Cerbe &Wilhelms, 2011). The volume-flow rate of air can be calculated using the air-flow rate (measured by TESTO vans probe) and the diameter of outlet at the air exhaust side (obtained from the specification sheet of the TESTO vans probe).

$$\dot{m} = \frac{\dot{v} \cdot p}{R_D \cdot t} \cdot \frac{1}{(0.622 + x)} \tag{5}$$

Where:

$\dot{v}$: Volume flow rate of air (m^3/s)*

p: Barometric pressure (Pa)

R_D: Specific gas constant water vapor, 461 J/kg*K

t: Air temperature (K)

x: Absolute humidity ($kg_{water}/kg_{dry\ air}$)

$\dot{m}$: The mass flow rate of air (kg/s)

(b) The heat distribution pattern (‘conditioned space/ceiling plenum split’**)**

Equation (6) is used to calculate the ‘conditioned space/ceiling plenum split’.

$$R_{room/ceiling} = \frac{\dot{Q}_{room}}{\dot{Q}_{ceiling}} \quad (6)$$

Where:

$R_{room/ceiling}$: The heating power split of tested luminaires

$\dot{Q}ceiling$: heating power in the ceiling plenum cavity

$\dot{Q}room$: heating power in the room cavity

(c) Extract reheating energy from annual heating energy results

In Energy plus simulations, the space heating energy (in heating season) and the reheating energy of the air-conditioning system (in cooling season) are automatically counted as one output value for annual heating energy consumption. Therefore, the reheating energy can be extracted by the following process in Equation (7).

$$Q_{Reh} = Q_{h,annual} - Q_{heating\ only} \quad (7)$$

Where:

Q_{Reh}: Reheating energy generated in cooling season (GJ)

$Q_{heating\ only}$: Heating energy only for space heating (GJ)*

$Q_{h,annual}$: Annual heating energy (GJ)

It is worth mentioning that the $Q_{heating\ only}$ can be obtained from the annual heating energy results of Energy Plus simulation of the tested building modeling containing only heating equipment (e.g., electric coil, gas heating, hot water heating) in its HVAC system (which means the cooling equipment and reheat system shall be removed before running simulation).

3.1.2 Research Assumptions

Due to some limitations existed in the Cold Room experiments and Energy Plus simulations, as detailed below, the present study was conducted based on the following assumptions:

Assumption #1: Heat gain from LED driver is not counted in the calculation.

The prototype LED luminaire with new architecture of "Heat Arrangement of LED Arrays in Low Profile" developed in KU Lighting Research Lab was used to verify the idea that the new architecture of LEDs can redirect heat flux toward the front to utilize more heat generated by LED chips in the room space. Since the prototype LED was an incomplete product without an attached LED driver (instead, a DC power source was used), there was no way to count heat gains from LED driver into the total heating power of prototype LED luminaires. Therefore, for prototype LED fixtures tested in this study, we assumed no heat gain from LED drivers was counted in the calculation. To be consistent, LED drivers and/or DC powers connected to all other luminaires tested in this study were put outside of the calorimeter to power LEDs inside.

Assumption #2: Using the calculated heating power of the LED luminaires as the input values of lighting load (w/m^2) in Energy Plus simulation.

Based on the design of the calorimeter, heat gain in each cavity from the tested lighting fixtures was calculated using air temperature difference measured with air temperature sensors. Using available calorimeter's output values, it was impossible to calculate the 'radiative/convective split' of tested LED luminaires in the calorimeter. Fortunately, the heat contribution from radiation to the temperature measurement in calorimeter was negligible because LEDs have almost zero IR radiation in the forward direction (different from conventional light sources). Also, the inside surfaces of the calorimeter were covered with aluminum foils with low emissivity. The temperature sensors also had a very tiny surface area and made of low emittance materials (Figure 12). Since the focus of this study was the thermal performance of LED fixtures, the lighting power density (W/m^2) in the Energy Plus would only contain pure heating power generated from luminaires with the fraction of visible light (in a range 0-1), while the fraction of radiant (in a range 0-1) were set to 0 (Figure 13).

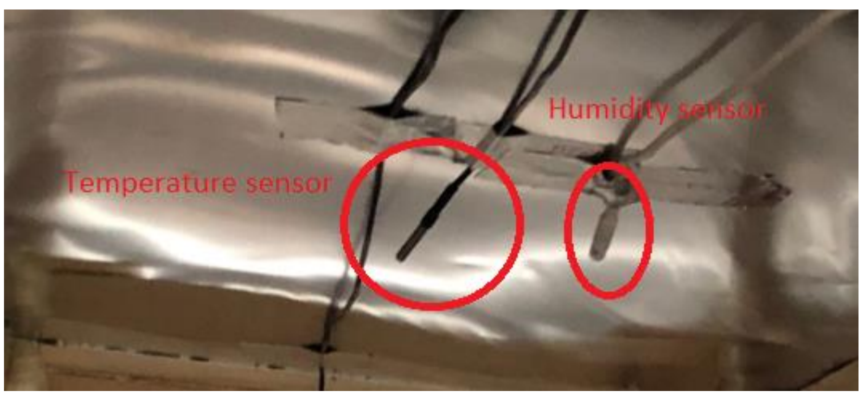


Figure 13 Two types of sensor installed in the calorimeter with aluminum foil covered interior surfaces

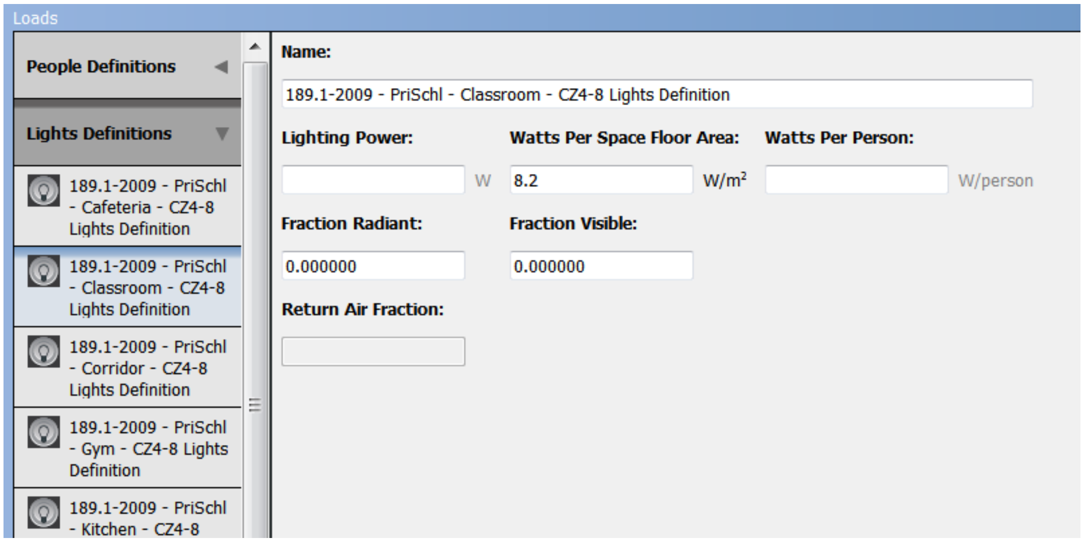


Figure 14 Lights definitions setting page in Energy Plus

Assumption #3: In Energy Plus simulation for LEDs with new lighting arrangement, in cooling season, the heating power of LED luminaire in room cavity is assumed to be 0, which is otherwise taken as increased cooling load by the Energy Plus software, to realize the energy saving design that utilizes the harvested room-portion of heat generated by LEDs as a supplemental reheating power of the building air-conditioning system.

The LED heat generated by the new LED luminaires and harvested in the room space can be used to supplement space heating in heating season, which is relatively easy to simulate in Energy Plus. Nonetheless, in cooling season, the heat gain from the conventional lighting system often increases the cooling load of building HVAC system. To change this situation, the installation and operation of future solid-state lighting system should be integrated with the building HVAC system. The innovation of the new integrative LED luminaires is to harvest the otherwise wasted heat generated by the LEDs and then utilize the heating power of luminaires in the room space to warm up the chilled air as a supplemental re-heating power to the reheating system of the building air conditioning system in cooling season. Therefore, when this integrative illumination and air-conditioning system is applied in buildings, the heating power of LED luminaires (calculated from the laboratory experiments results) harvested in the room space shall be considered as a supplemental reheating power instead of an undesirable cooling load in cooling season. Accordingly, in Energy Plus simulation, the heating power of LED luminaire in room cavity shall be set to 0, which is otherwise taken as increased cooling load by the Energy Plus software, to realize the energy saving design that utilizes the room-portion of heat generated by LEDs as a supplemental reheating power in the cooling season.

Assumption #4: In Energy Plus simulation, all four luminaires tested in the laboratory have approximately the same heating power.

Different LED luminaires often have different thermal features (e.g., heating power, heat distribution), resulted from different system architectures, different materials, different LED chips and their layout on the MCPCB board, and different insulation, etc. Thus, even with the same nominal wattage, the four LED luminaires tested in the laboratory may not have the same value of heating power harvested in the room space.

One goal of the present study was to validate that utilizing the room-portion of heat generated by LED luminaires that is harvested in the room space can save annual heating and cooling energy of buildings. To that end, the annual heating and cooling energy consumptions of different LED luminaires installed in the primary school classroom were simulated in Energy Plus and compared. The primary variable in Energy plus simulation shall be the heat distribution pattern ('conditioned space/ceiling plenum split') of those luminaires. All other variables, including the heating power of each LED luminaire, may have mixed effects on the simulation results, thus, shall be excluded by assigning preset values to those confounding variables. Therefore, the total heating power (room portion plus ceiling portion) is set to 50W for all luminaires used in Energy Plus simulation.

3.2 Pilot study

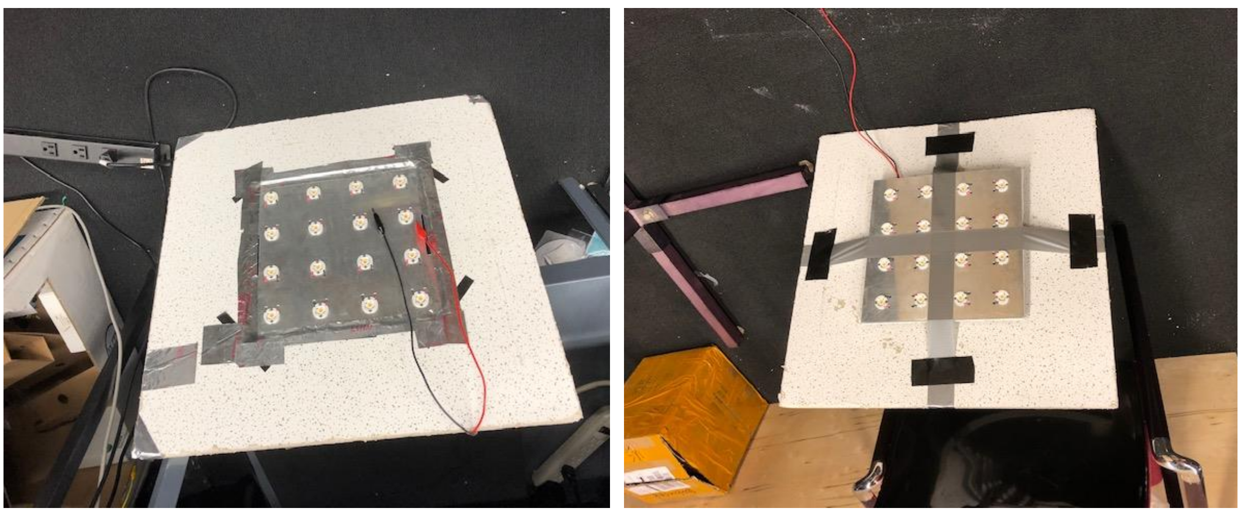
A pilot study was conducted to collect useful information in preparation for the formal experiments, such as potential issues that may affect the formal experiments, which need to be identified and resolved in the pilot study. Meanwhile, all sensors were checked to ensure they would all be under normal working condition in the formal experiments. The calculation process for data treatment was also verified in the pilot study.

3.2.1 "Dark-room" experiments

The pilot experiment was conducted in the Dark Room (1152 Learned Hall) to explore key factors that may have essential influence on experiment results and/or output values. A total of ten tests were conducted in the Dark Room, as shown in Table 2, including five tests of surface-mounted LED luminaires and another five tests of ceiling-recessed LED luminaires. Figure 15 shows the prototype LED with two typical constructions: ceiling recessed (15-a) and surface mounted (15-b) in this study. Figures 16-19 are the actual luminaires testing process in the Dark Room under room temperature.

Table 2 Configurations of LED luminaires' tests in pilot study

Test case #	Luminaire type	Mounting method	Nominal Power
1	Prototype LED	Ceiling Recessed	57.6W
2	Prototype LED	Ceiling Recessed	57.6W
3	Prototype LED	Ceiling Recessed	57.6W
4	Prototype LED	Ceiling Recessed	57.6W
5	Prototype LED	Surface Mounted	57.6W
6	Prototype LED	Surface Mounted	57.6W
7	Prototype LED	Surface Mounted	57.6W
8	Prototype LED	Surface Mounted	57.6W



(a) (b)

Figure 15 The same prototype LED luminaires tested in the calorimeter were mounted differently in different tests, (a) ceiling-recessed, (b) surface-mounted

Figure 16 The prototype LED luminaire surface mounted on the ceiling of the calorimeter chamber

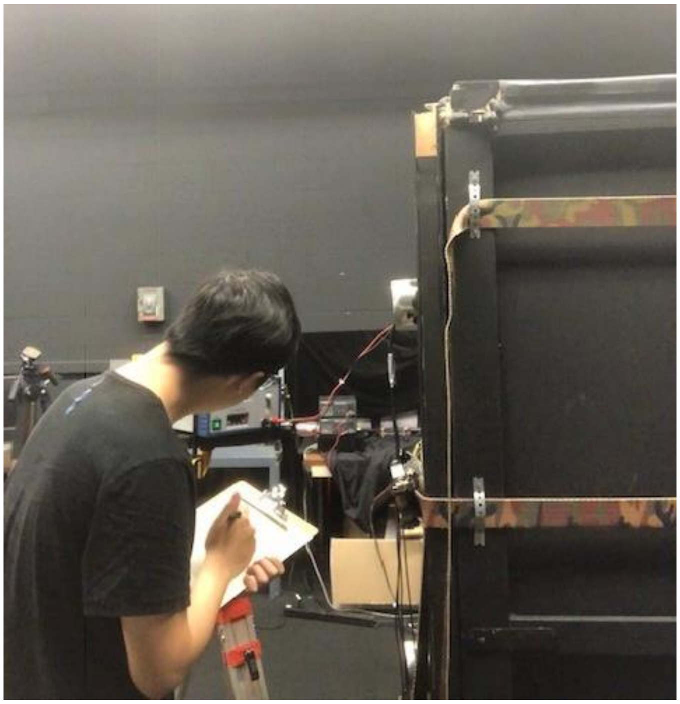


Figure 17 Data recording during tests

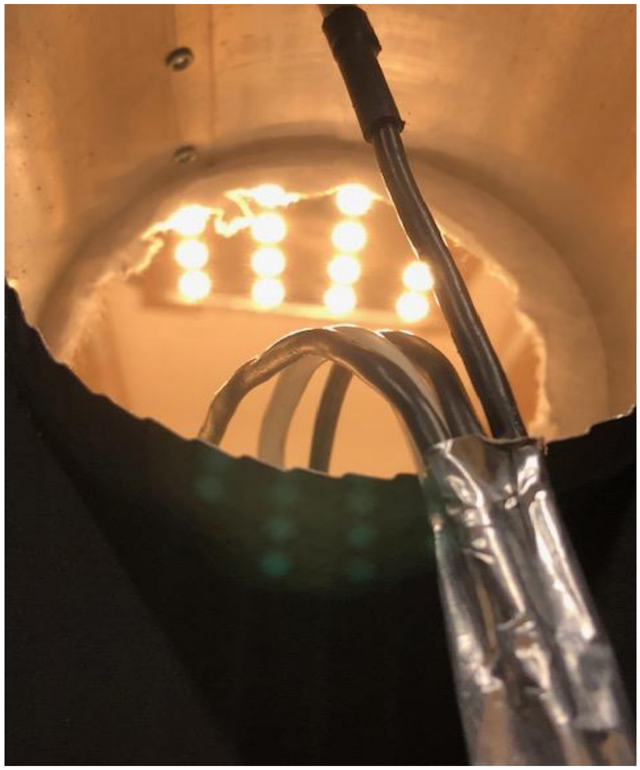


Figure 18 Temperature sensor mounted at air intake of the room cavity

Figure 19 The ceiling recessed prototype LED luminaire in the calorimeter

3.2.2 Data treatment and results

Table 4 shows the calculation results of heat output of LED luminaires from the calorimeter with trusted input values. These input values are either direct measured by calorimeter (e.g. temperature difference between air-intake and air-exhaust, relative humidity inside of the calorimeter, air-flow rate) or obtained from authority agency (e.g. Climate data from local weather station website). Barometric pressure (Table 3) was downloaded from weather station website (weather.com). Other values measured inside the calorimeter, including relative humidity (%), air-flow rate (m/s) and air temperature (°F/°C), were readout after heat balance was reached inside the calorimeter. Water vapor saturation pressure (Figure 19) was obtained from water saturation pressure chart.

Table 3 Barometric pressure (Daily weather report, available at *weather.com*, 2018)

Barometric Pressure, Lawrence, KS		
Date	**In Hg**	**kPa**
08/21/18	30.12	101.9900
08/22/18	30.30	102.6079
08/27/18	29.80	100.9147
08/28/18	29.80	100.9147
08/29/18	30.10	101.9306
09/05/18	30.10	101.9306
09/07/18	30.10	101.9306
09/10/18	30.00	101.5920
09/12/18	30.00	101.5920
09/14/18	30.00	101.5920
09/28/18	30.10	101.9306
09/27/18	30.10	101.9306
10/01/18	30.00	101.5920
10/04/18	30.10	101.9306
10/05/18	30.10	101.9306
10/03/18	30.00	101.5920
10/08/18	30.00	101.5920
10/10/18	30.10	101.9306

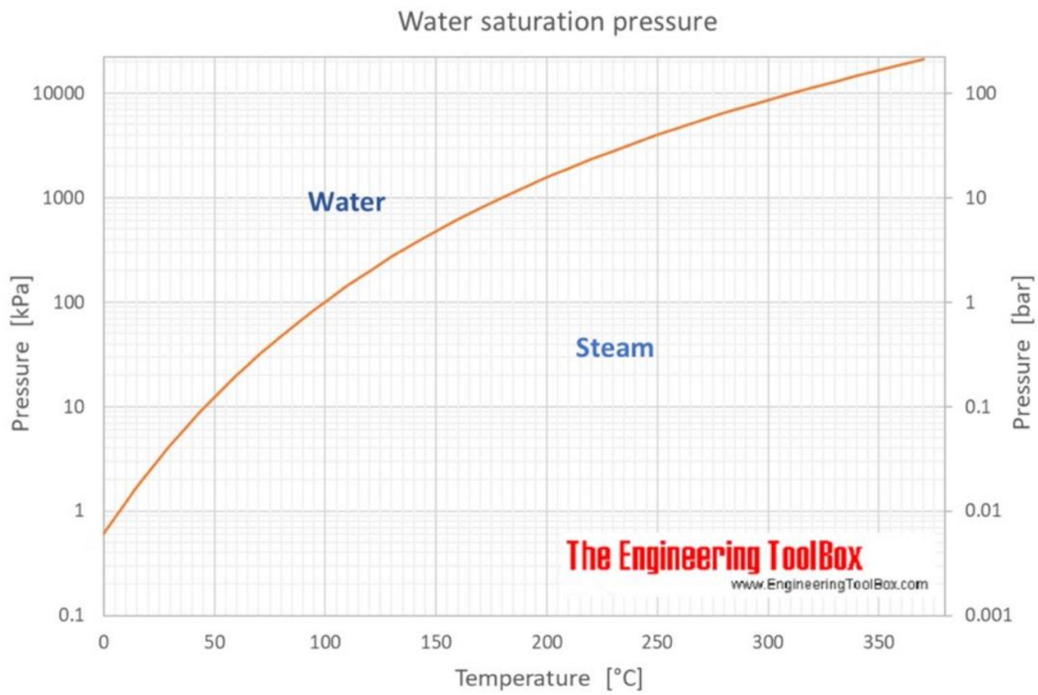


Figure 20 Water vapor saturation pressure chart [Engineering ToolBox, (2001). Available at: https://www.engineeringtoolbox.com, Dec 2018]

Table 4 lists all the test results from the pilot study experiments with different configurations (Table 2). There are three issues found in Table 4, which need further discussions. Firstly, the ratio of the wattage loss of the calorimeter (due to thermal leakage through imperfect insulation, the output wattage is less than input wattage) to the total input power is not a constant value, even for the same luminaires under same testing configurations (as shown in Test 1 and Test 2). Secondly, the 'conditioned space/ceiling plenum split' of the same LED luminaires was not a constant value when obtained from different tests in the calorimeter under the same configuration of experiment (e.g., with the same mounting method and the same input power, as in Test 5 and Test 7). Thirdly, in Test 5, the wattage loss was a negative value, which is incorrect since the output heating power cannot exceed the input heating power according to the first law of thermodynamics. Those three issues observed in the pilot study were caused by the uncontrolled varying testing environment (e.g., room temperature and humidity) in the Dark Room. During the process of the experiments conducted in the Dark Room, the AC unit in the Dark Room kicked in from time to time resulting in fluctuating room temperature. The random occupancy of other users who accessed the Dark Room during the experiments also resulted in unknown impact on the room temperature, humidity and air circulation that would affect the ongoing experiments. Those uncertainties could be avoided in a well-controlled test environment. All those three issues were overcome in the follow-up formal experiment carried out in the well-controlled space, “Cold Room”.

Table 4 Results from the “dark room” experiments

Test #	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8
Date	08/21/18	08/22/18	08/27/18	08/28/18	08/29/18	09/05/18	09/07/18	09/10/18
Input power (W)	26.30	26.30	30.60	54.0	54.0	63.0	54.0	54.0
Total output power (W)	24.90	21.39	26.74	54.43	49.78	55.97	46.11	45.92
Power in room (W)	14.23	12.22	15.06	27.21	23.91	33.81	29.99	29.40
Power in ceiling (W)	10.67	9.17	11.68	27.21	25.88	22.16	16.11	16.52
Wattage loss (W)	1.40	4.91	3.86	-0.43	4.22	7.03	7.90	8.08
Wattage loss/total (%)	5.3%	18.7%	12.6%	-0.8%	7.8%	11.2%	14.6%	14.9%
“room/ceiling” split	57/43	57/43	56/44	50/50	48/52	60/40	65/35	64/36

3.2.3 Recommended improvements for formal experiment

The Dark Room was not a well-controlled space for maintaining constant environmental temperature and humidity over time. During the tests, the room temperature and humidity were varying because of the unpredictable working condition of the independent AC unit, resulting in unstable temperature balance point of the calorimeter (the temperature difference between air-intake and air- exhaust is no longer changing), which largely affected the accuracy of measurement results for data treatment.

Following are three recommendations to solve those three issues observed in the pilot study for improvements in the follow-up formal experiment to be conducted in the Cold Room.

(a) Each experiment should be conducted in a closed, well-controlled and undisturbed space.

(b) To reach the heat balance of the calorimeter, each experiment should be lasted for at least 5 hours.

(c) The back surface of the prototype LED luminaire needs to be covered with aluminum foil, making it the same construction for minimum heat radiation as those commercial LED luminaires with aluminum housing.

Since the Cold Room installed with special air-conditioning equipment is a well-controlled space with constant room temperature and relative humidity, which are adjustable, those three issues aforementioned in the pilot study would not be observed in the Cold Room experiments. Additionally, the formal experiments in Cold Room would not be disturbed to prevent external interference on the stable room temperature and the relative humidity. Each experiment would last at least 5 hours to ensure that the calorimeter reaches heat balance point (ongoing heat generated by tested LED luminaires is quickly removed by controlled air-flow that reaches an equivalence status).

3.3 Experiments in the Cold Room

3.3.1 Introduction

The Cold Room (G455A) in M2SEC building is a well-insulated laboratory with an interior environment control system providing stable room temperature and relative humidity, which are preset values. The interior air temperature of the Cold Room can be set from 0°C to 30°C with an accuracy of one decimal and relative humidity inside could be keep at range 45%-50%. Nonetheless, it is worth mentioning that the environment control system stabilizes interior air temperature and relative humidity by using strong circulating air-flow, which may increase the heat loss of the calorimeter due to increased convection occurred on exterior surface of the calorimeter.

Figure 20 shows the Cold Room laboratory and the outside control panel that enable adjustment of the interior air temperature without opening the door causing undesired external interference on the ongoing experiment. Figure 21 shows the setup of the experiments in the Cold Room. All air pipes of the calorimeter were connected to fans put on an equipment cart. Temperature and humidity sensors in the calorimeter were connected to HUBO data logger and air-flow sensors connected to TESTO-480 data logger put on the equipment cart.

(a) (b)

Figure 21 The Cold Room laboratory, (a) the control panel, (b) a watch window on the door of the Cold Room

Figure 22 Setup of the calorimeter in the Cold Room

To keep an isolated environment in the Cold Room, the door was closed for ongoing experiments to avoid any unnecessary external interference until a set of experiments were completed without need of changing fixtures or mounting methods (e.g. testing surface-mounted custom-designed LED luminaire under four different air temperatures). The DC power, patch panel and data-loggers, were locked inside of the Cold Room connected to the electricity outlet and laptop (for data recording) through a dedicated wire hole insulated with insulation materials to outside of the "cold room" (Figure 23). The ongoing experiment inside the Cold Room was observed through a double-glazing window with anti-condensation design (Figure 24).

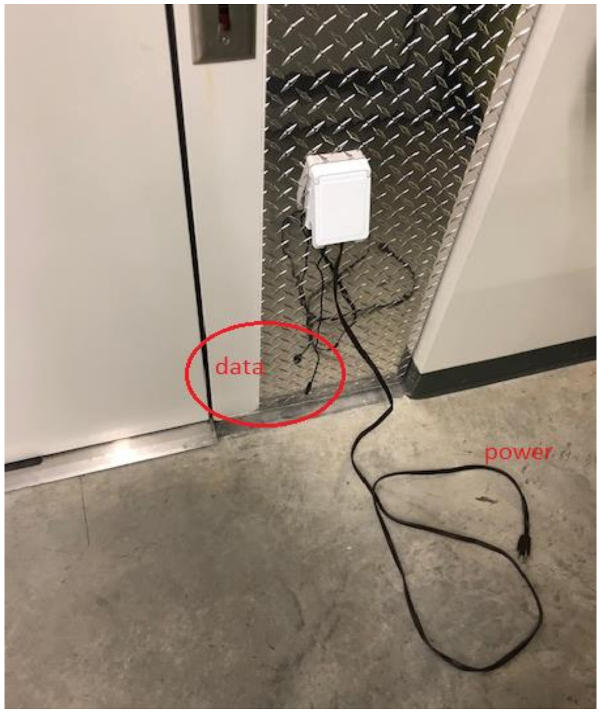


Figure 23 Power cable and data wire

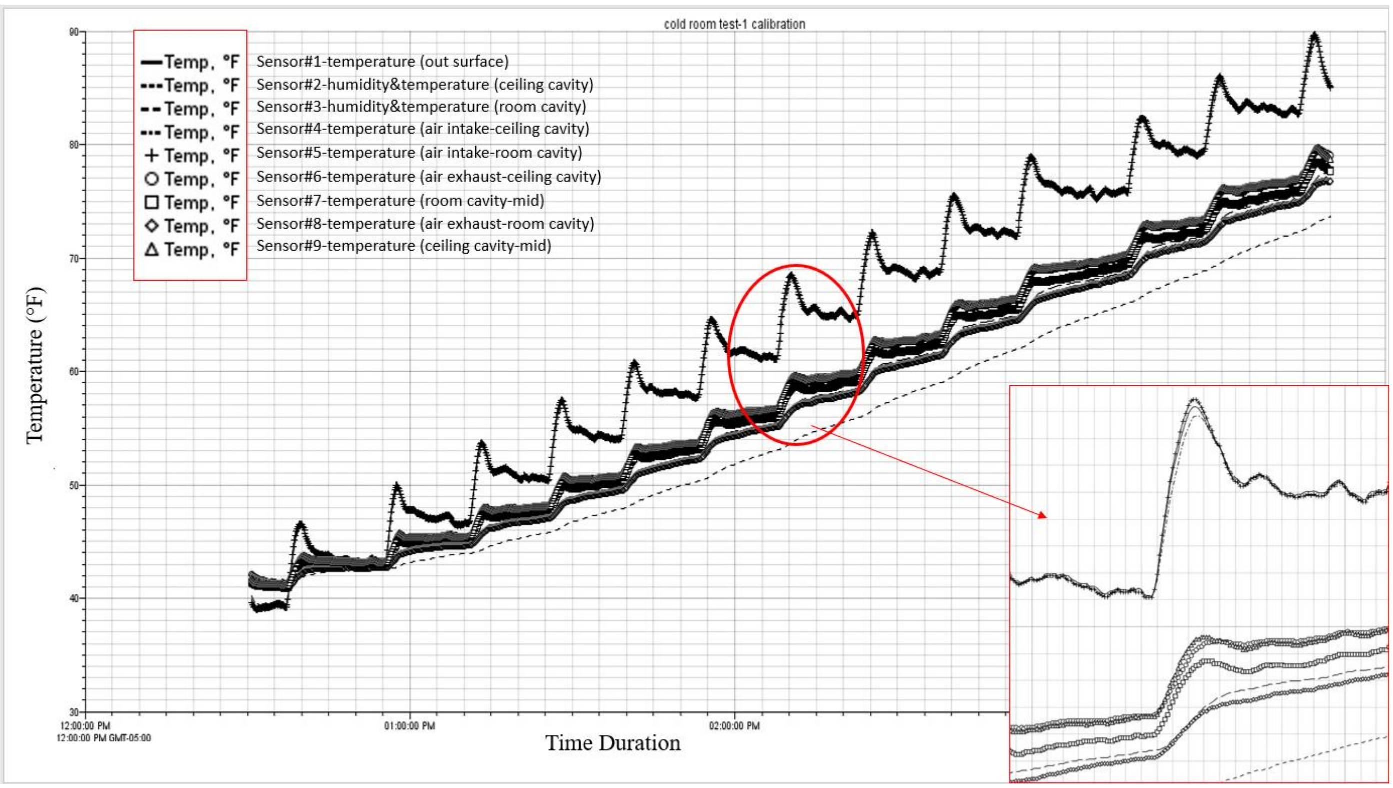
Figure 24 Anti-condensation observation window

3.3.2 Calibrations

Two calibrations were conducted before testing LED luminaires in the Cold Room. First, the room temperature of the Cold Room was measured by three temperature sensors and checked with the interior temperature value shown on the control panel. When the two readings did not agree, the reading of temperature sensors were calibrated to that of the control panel.

As shown in Figure 24, the calibration was conducted at a reasonable range of the ambient temperature from 4°C to 30°C with a step of 2°C increase. It was found that the data curves of three sensors (one mounted at the top air-intake for measuring the air temperature of the ceiling cavity of the calorimeter, one at the down air-intake for measuring the air temperature of the room cavity, the third one mounted outside of the calorimeter in the Cold Room for measuring the cold room temperature) were very close to each other at the same trend of changes. Their read-out temperatures (in °C) were also very close to the room temperature values read from the Cold Room control panel.

However, as shown in Figure 24, the data curves of other six temperature sensors inside the calorimeter showed a “lagging pattern” behind the changes of the room temperature of the Cold Room, indicating the air temperature inside the two Calorimeter cavities did not change immediately with changes of the room temperature of the Cold Room, caused by thermal resistance of the calorimeter. To solve this problem, longer testing time was necessary for components inside the calorimeter reaching thermal equilibrium to reduce the lagging pattern caused by thermal mass of the calorimeter. Thus, a second experiment was conducted with increased room temperature of the Cold Room from 12.5°C to 21°C (step 1) and then from 21°C to 29.5°C (step 2) to test the temperature sensors read-out from one temperature balance state to another one. At each step, after the Cold Room temperature was adjusted to the new value (21°C at step 1, 29.5°C at step 2), the calorimeter was allowed for 6 hours to reach its temperature balance to solve the “lagging” issue of the six temperature sensors inside. As shown in Figure 25, it was found that all sensors were working normally according to their read-out temperatures which were the same value when the thermal balance point was reached.



*Format of sensors: sensor number-sensor’s type- (sensor’s location)

Figure 25 Results of the first calibration: temperature increased from 4°C to 30°C (39°F to 86°F) with each step is 2°C

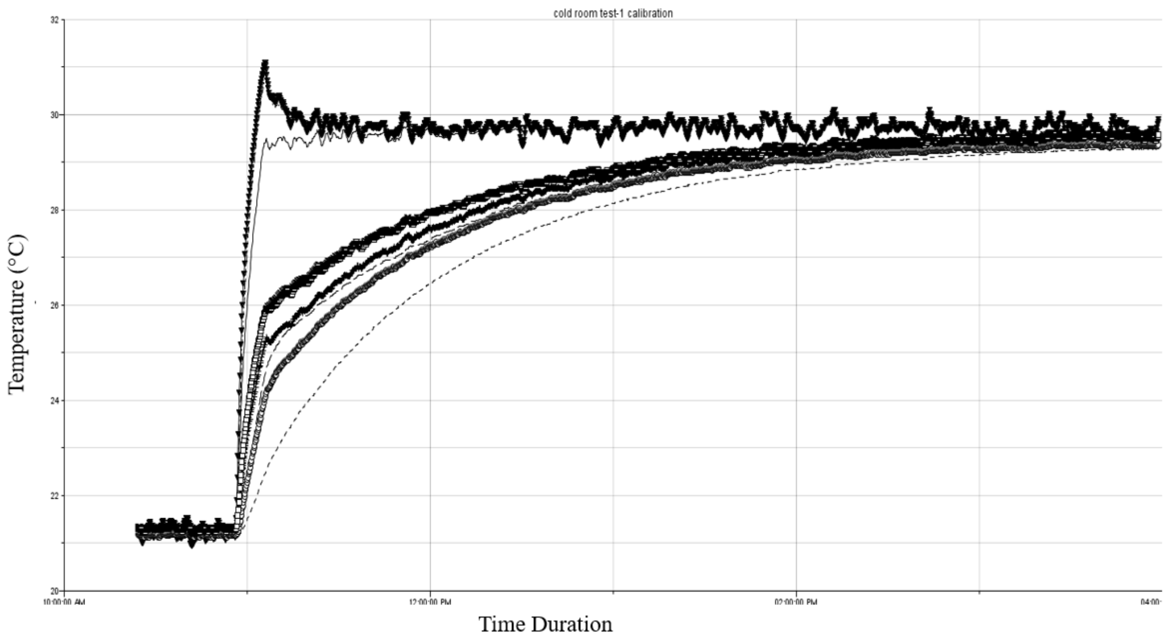


Figure 26 Calibration of temperature sensors with tested room temperature of 21.0°C to 29.5°C (70°F to 85°F).

In addition to the first calibrations of the temperature sensors mounted inside the Calorimeter, a second calibration was conducted for compensation of the thermal loss of the calorimeter. Diederich (2017) already conducted several experiments in 2017 to determined heat-loss rate of the calorimeter. In his experiments, a cartridge heater (pure heat source with 100% input power transferred to heat, as shown in Figure 27) was mounted inside the calorimeter to obtain heat loss of the calorimeter. Based on previous studies of the commissioning of the calorimeter, 11% of wattage loss is defined as an acceptable measurement error (Diederich, 2017). A similar experiment was conducted in 2018 to repeat Diederich's calibration procedure to make sure the calorimeter was well-insulated and still in good working condition before the formal experiment. Figure 28 shows the temperature readings over the calibration process of the calorimeter heat loss over six hours. As shown in Table 5, the input power of the cartridge heater was 35.31 W (recorded from the DC power) while the calculated heat output was 32.61 W based on the measured values of the calorimeter after thermal equilibrium was reached. Therefore, the heat loss rate was calculated as 7.6% in this calibration test, as shown in Table 5, which was less than 11% acceptance level set by Diederich's experiment, showing the calorimeter was still in normal working condition ready for formal experiments.

Table 5 Results of the cartridge heater tests in the Calorimeter

Calibration test-cartridge heater	reference value	Measured value
Room Cavity	N.A.	12.27 W
Celling Cavity	N.A.	20.34 W
Total Output	N.A.	32.61 W
INPUT	U=32 V, I= 1.1 A	35.3 W
ROOM T	20.0 °C (68 °F)	20.38 °C (68.7°F)
Wattage loss	N.A.	2.69 W
Heat loss ratio	N.A.	LOSS/T=7.6%

Figure 27 The pure heat source (cartridge heater) mounted in the Calorimeter

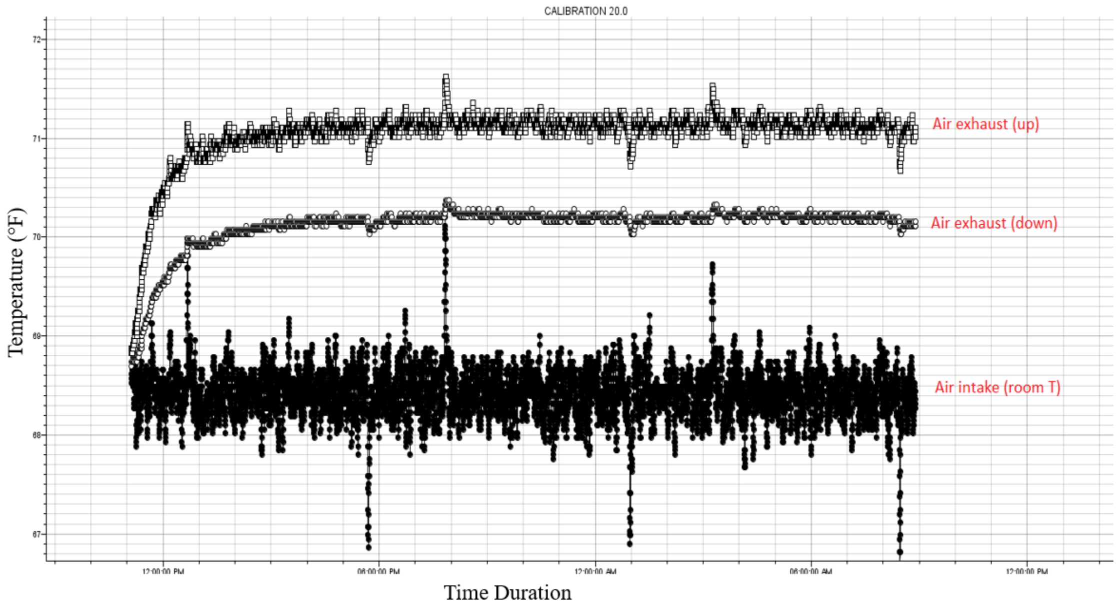


Figure 28 The Calibration of calorimeter heat loss at room temperature of 20°C, showing the calorimeter reached thermal equilibrium over 6 hours

With the three calibrations completed, the calculated heat output from the LED luminaire tested in the calorimeter could be trusted values. Temperatures measured with those sensors had a satisfied accuracy of within ±0.5°F, which reflects the difference between the temperature measured by the sensors mounted inside and outside of the calorimeter and the preset value on the “cold room” control panel. The heat loss of the calorimeter was 7.2% (cartridge heater at 35W input), which is in the tolerance range (within ±10%) based on previous study by Simon Diederich in 2017. As a result, the calorimeter was considered in good working condition and ready for the formal experiments in the Cold Room.

3.3.3 Formal experiments and the results

The purpose of the Cold Room experiments was to measure the heat distribution pattern ('conditioned space/ceiling plenum split') of the tested LED luminaires with two different mounting methods (ceiling recessed versus ceiling surface mounted). Table 6 shows a complete lists of eight tests in this experiment, including ceiling-recessed prototype LED fixture tested in summer and winter conditions (Tests 1 and 2), ceiling surface-mounted prototype LED fixture in summer and winter conditions (Tests 3 and 4), and two commercial LED fixtures either ceiling-recessed (Tests 5 and 6) or surface-mounted (Tests 7 and 8) tested in summer and winter conditions. Each test contained four separate trials under four different room temperatures: 68°F, 72°F, 74°F, 78°F (ASHRAE standard 55 2010). As summarized in Table 7, the Cold Room temperature was set to 68°F and 72°F (ASHRAE recommended lowest and highest acceptable indoor temperatures in winter) to simulate luminaires working in the winter room's conditions, while 74°F and 78°F in summer room's conditions (ASHRAE recommended). During the experiment, to exclude external interference on the tests, the Cold Room was locked until one set of experiment was completely done under different room temperatures without necessary changes of luminaires and their mounting methods.

Table 6 "Cold room" luminaire tests configurations

Test #	Tested Luminaires	Mounting method	Nominal Power (Labeled)	Season for Simulated Room Condition	Acceptable Temperature Lower limit	Acceptable Temperature Upper limit
Test 1	Prototype LED	Ceiling Recessed	57.6 W	Summer	20 °C (68 °F)	22.2 °C (72 °F)
Test 2	Prototype LED	Ceiling Recessed	57.6 W	Winter	23.3°C(74°F)	25.6°C(78°F)
Test 3	Prototype LED	Surface Mounted	57.6 W	Summer	20 °C (68 °F)	22.2 °C (72 °F)
Test 4	Prototype LED	Surface Mounted	57.6 W	Winter	23.3°C(74°F)	25.6°C(78°F)
Test 5	Commercial LED	Ceiling Recessed	50 W	Summer	20 °C (68 °F)	22.2 °C (72 °F)
Test 6	Commercial LED	Ceiling Recessed	50 W	Winter	23.3°C(74°F)	25.6°C(78°F)
Test 7	Commercial LED	Surface Mounted	2*25 W	Summer	20 °C (68 °F)	22.2 °C (72 °F)
Test 8	Commercial LED	Surface Mounted	2*25 W	Winter	23.3°C(74°F)	25.6°C(78°F)

Table 7 Guidelines of acceptable room temperature, excerpts (Thermal environment Condition for Human Occupancy, ASHRAE Standard 55, 2010)

Type of space	In Fahrenheit (°F)		In Celsius (°C)	
	Summer	Winter	Summer	Winter
residences, apartments	74-78	68-72	23-26	20-22
classroom, courtroom	74-78	68-72	23-26	20-22
school dining room	75-78	65-70	24-26	18-21
ballrooms	70-72	65-70	21-22	18-21
retails shop, supermarket	74-80	65-68	23-27	18-20
medical operating rooms	68-76	68-76	20-24	20-24
toilet room, service room	80	68	27	20
locker room	75-78	65-68	24-26	18-20

In addition, the controlled air-flow rates of both ceiling and room cavity were calibrated to approximately the same value before a new set of experiment was started. Figure 28 shows the real time measurement of the controlled air-flow. The data curve in red is for ceiling cavity and that in purple is for room cavity.

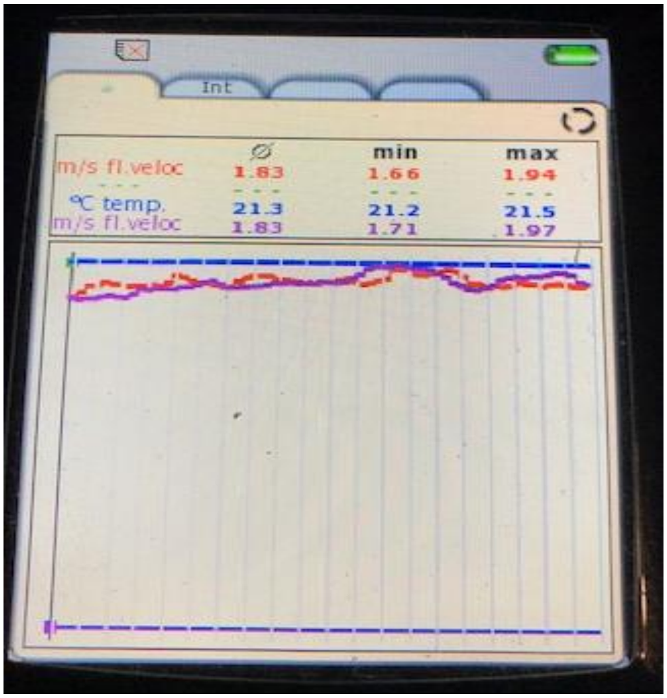


Figure 29 The real time measurement of the controlled air-flow rate in ceiling cavity (red) and room cavity (purple).

Tables 8-11 are the summarized results of eight luminaire experiments conducted in the Cold Room. Each table showing one luminaire with four typical room temperature (upper limit and lower limit of acceptable room temperature in summer and winter). A complete list of outcomes with a detailed calculation process was available in Appendix 1 *"calculation sheet of cold room luminaires' tests"*.

Based on the results shown in Table 8, the heat distribution pattern ('conditioned space/ceiling plenum split') of the ceiling-recessed prototype LED luminaire was determined as of **60.4/39.6**, the average of similar values obtained in the four tests. Similarly, the 'conditioned space/ceiling plenum split' was averagely **69.6/30.4** for the ceiling surface-mounted prototype LED luminaire (Table 9), **47.2/52.8** for the ceiling-recessed commercial LED luminaire (Table 10), and **58.1/41.9** for the surface mounted commercial LED luminaire (Table 11).

Table 8 Results of the **ceiling recessed prototype** LED luminaire testing

TEST #	1-a	1-b	2-a	2-b
Room Temperature °C (°F)	20.0 °C (68 °F)	22.22°C(72°F)	23.33°C(74°F)	25.56°C(78°F)
Measured Room Temperature or Temperature of Air intake °C (°F)	20.28°C (68.5°F)	22.56°C (72.6°F)	23.61°C (74.5°F)	25.83°C (78.5°F)
Air-flow rate (m/s)	1.78	1.78	1.78	1.78
Temperature Difference in room cavity(°C)	1.85	1.90	1.87	1.88
Temperature Difference in ceiling cavity(°C)	1.24	1.23	1.21	1.24
Measured heating Power in room cavity (W)	30.40	31.23	30.79	30.91
Measured heating Power in ceiling cavity (W)	20.38	20.21	19.94	20.42
Conditioned space/ceiling plenum split in each test	59.9/40.1	60.7/39.3	60.7/39.3	60.2/39.8

Table 9 Results of the **surface mounted prototype** LED luminaire testing

TEST #	3-a	3-b	4-a	4-b
Room Temperature °C (°F)	20.0 °C (68 °F)	22.22°C(72°F)	23.33°C(74°F)	25.56°C(78°F)
Measured Room Temperature or Temperature of Air intake °C (°F)	20.28°C (68.5°F)	22.42°C (72.3°F)	23.61°C (74.5°F)	26.04°C (78.8°F)
Air-flow rate (m/s)	1.78	1.78	1.78	1.78
Temperature Difference in room cavity(°C)	2.18	2.17	2.13	2.16
Temperature Difference in ceiling cavity(°C)	0.95	0.97	0.92	0.93
Measured heating Power in room cavity (W)	35.72	35.64	35.98	35.57
Measured heating Power in ceiling cavity (W)	15.62	15.93	15.09	15.30
Conditioned Space/Ceiling Plenum split	69.6/30.4	69.1/30.9	69.9/30.1	69.9/30.1

Table 10 Results of the **ceiling recessed commercial** LED luminaire testing

TEST #	**5-a**	**5-b**	**6-a**	**6-b**
Room Temperature °C (°F)	20.0 °C (68 °F)	22.22°C(72°F)	23.33°C(74°F)	25.56°C(78°F)
Measured Room Temperature or Temperature of Air intake °C (°F)	20.44°C (68.8°F)	22.67°C (72.8°F)	23.66°C (74.6°F)	25.74°C (78.3°F)
Air-flow rate (m/s)	1.68	1.68	1.68	1.68
Temperature Difference in room cavity(°C)	1.54	1.61	1.67	1.52
Temperature Difference in ceiling cavity(°C)	1.73	1.74	1.88	1.74
Measured heating Power in room cavity (W)	23.87	24.84	25.85	23.78
Measured heating Power in ceiling cavity (W)	26.81	26.85	29.10	27.22
Conditioned Space/Ceiling Plenum split	47.1/52.9	48.1/51.9	47.0/53.0	46.6/53.4

Table 11 Results of the **surface mounted commercial** LED luminaire testing

TEST #	7-a	7-b	8-a	8-b
Room Temperature °C (°F)	20.0 °C (68 °F)	22.22°C(72°F)	23.33°C(74°F)	25.56°C(78°F)
Measured Room Temperature or Temperature of Air intake °C (°F)	20.44°C (68.8°F)	22.67°C (72.8°F)	23.78°C (74.8°F)	25.89°C (78.6°F)
Air-flow rate (m/s)	1.65	1.65	1.65	1.65
Temperature Difference in room cavity(°C)	2.38	2.33	2.22	2.32
Temperature Difference in ceiling cavity(°C)	1.73	1.66	1.65	1.62
Measured heating Power in room cavity (W)	36.59	36.90	34.37	35.91
Measured heating Power in ceiling cavity (W)	26.60	25.58	25.55	25.08
Conditioned Space/Ceiling Plenum split	57.7/42.3	58.4/41.6	57.3/42.6	58.9/41.1

3.4 Computer-Aided simulation in Energy Plus

3.4.1 Design of Energy Plus simulation

A DOE's standard primary classroom equipped with those test LED luminaires was used for computer-aided simulation of the annual energy consumption. The model classroom has single floor, flat roof, located at Lawrence, KS, in ASHRAE climate zone 4. As shown in Figure 29, the room dimensions are approximately 11 m / 36 ft (length) by 8.5 m / 28 ft (width) by 3.05 m / 10 ft (height), with a ceiling plenum height of 0.91 m /3 ft. The model classroom was built in Sketch Up with Open Studio plugin and then input into Energy Plus. Constructions of the classroom was defined by Open Studio based on space type (primary school) and climate zone (4A). The general lighting was provided using 15 LED luminaires with nominal power of 50W/each. The calculated lighting power density (LPD) was 8.6 W/m^2 based on the gross room area (93.5 m^2) to be complied with the requirement of lighting codes for primary school classroom (IES handbook 10th edition, 2011). Weather data were obtained from the weather station of Topeka-Forbes AFB (*energyplus.net/weather)*, which is the nearest station to Lawrence.

The present study focused on investigation of the thermal performance of LED luminaires using the calculated heating power of the LED luminaires as the input values of lighting load (w/m^2) in Energy Plus simulation (*Assumption #2*). Thus, the light energy fraction of the tested LED luminaires was not counted in Energy Plus simulation. The heat fractions of the tested LED luminaires were approximated in Energy Plus by "pure heat sources" (still considered a definition of lighting fixtures in Energy Plus). The replacement "heat source" was then divided into two separate parts, with one assigned in the ceiling plenum and the other assigned in the room space to approximate the heat distribution pattern ('conditioned space/ceiling plenum split') of the tested LED luminaires obtained from the prior calorimeter experiments in the Cold Room. Figure 30 illustrate how to input the 'conditioned space/ceiling plenum split' of the tested LED luminaires in Energy Plus simulation. Figure 31 shows how to set the heating power of tested LED luminaires in the ceiling plenum space. In this simulation, all lighting fixtures were controlled on a typical lighting schedule of primary school classroom (Figure 29).

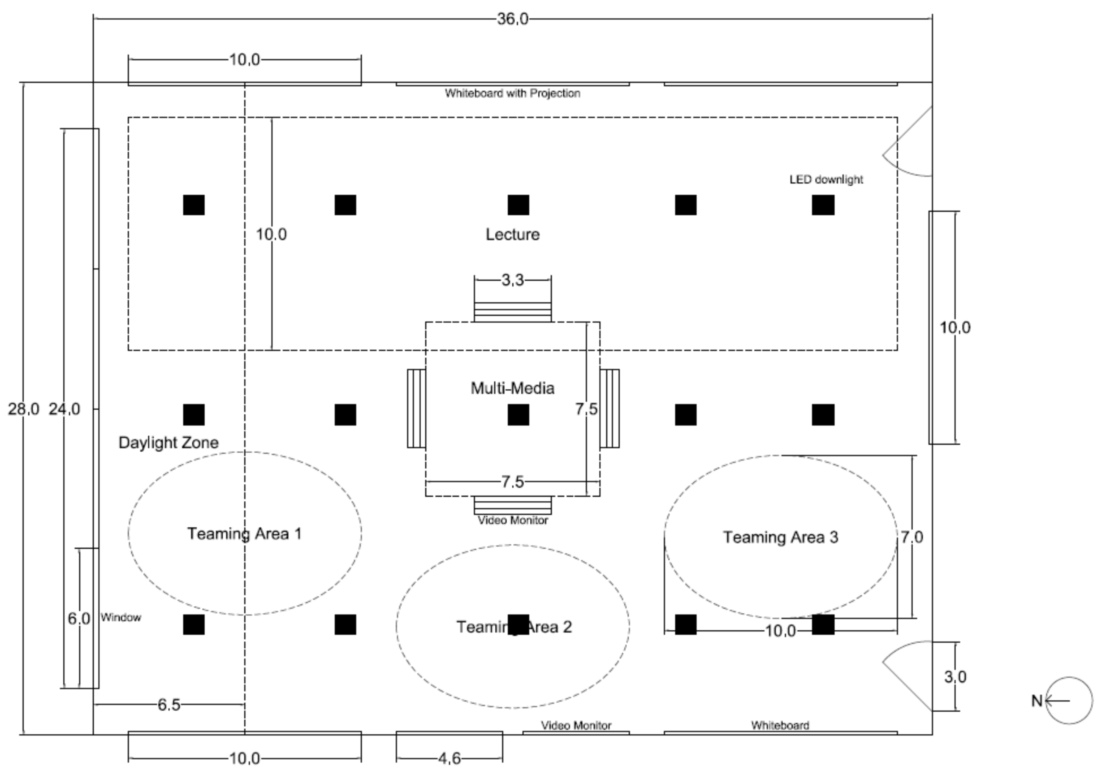


Figure 30 Floor plan and lights layout of the primary school classroom (Cai, 2015)

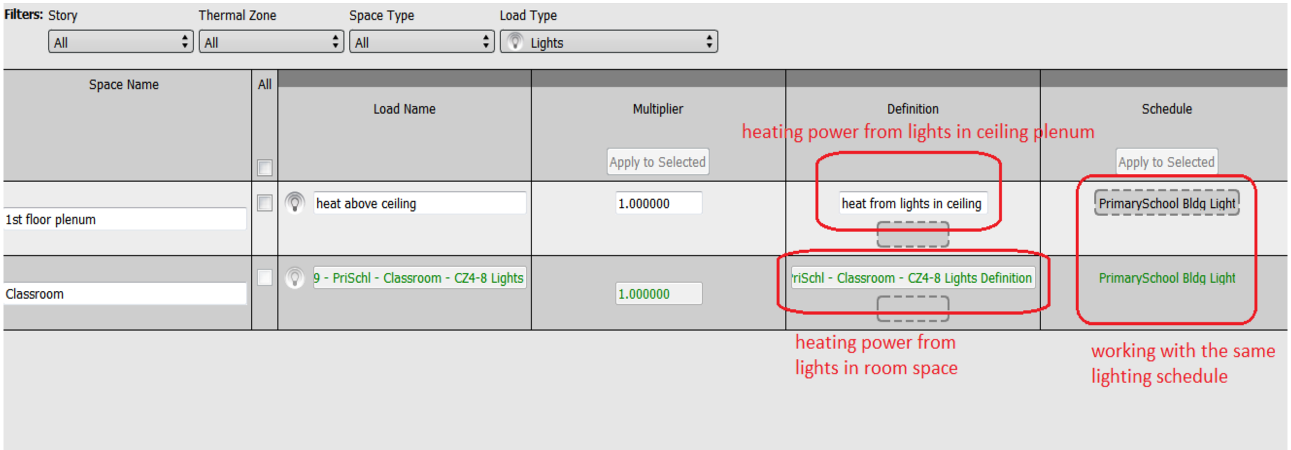


Figure 31 Define the heat distribution of luminaire

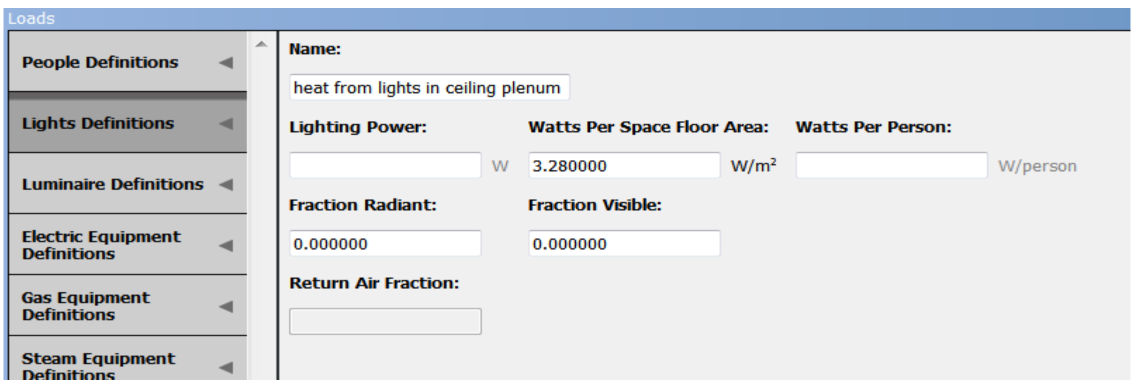


Figure 32 Define the heating power of luminaire in ceiling plenum

In Energy Plus simulation, the packed rooftop VAV (Variable Air Volume) with PFP (Parallel Fan Powered) boxes and Reheat was selected for the model classroom as its HVAC system with default heating and cooling schedule (through temperature set point) determined by the climate zone of the project site in Energy Plus, as shown in Figure 32.

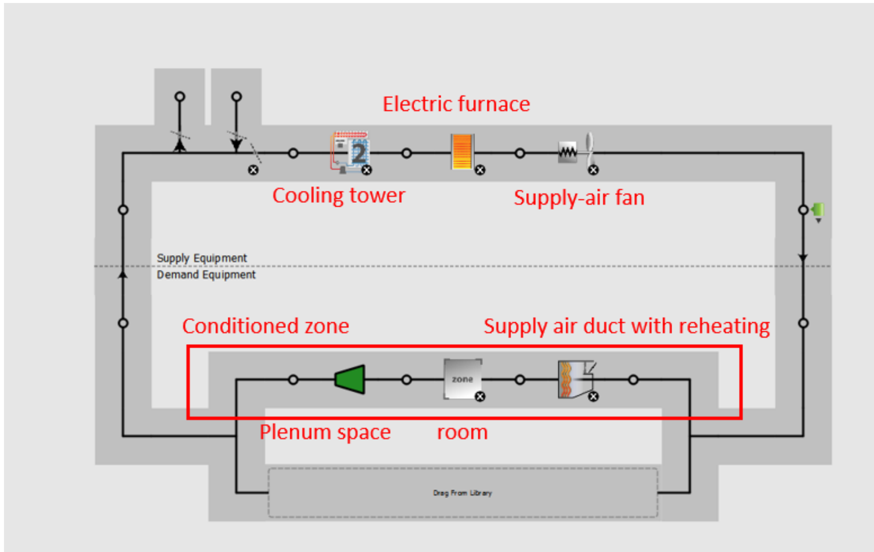


Figure 33 Defining the HVAC system of the model classroom in Energy Plus

3.4.2 Introduction to the modeling with the integrated lighting arrangement design

The custom-made prototype LED luminaire was used to verify a new energy-saving design in which the harvested LED heat in the room space is used as a supplemental reheating power to the re-heating coil of the HVAC system. The energy-saving design uses an integrative solid-state lighting & heating arrangement called "Heat Arrangement of LED Arrays in Low Profile". The energy-saving feature of the custom-made LED luminaire with "Heat Arrangement of LED Arrays in Low Profile" is to utilize the otherwise wasted portion of heat generated from prototype LED luminaires and trapped in the room space as part of reheat source. Therefore, assumption #3 was taken in Energy Plus simulation (*in cooling season, the heating power of LED luminaire in room cavity is assumed to be 0, which is otherwise taken as increased cooling load by the Energy Plus software, to realize the energy saving design that utilizes the harvested room-portion of heat generated by LEDs as a supplemental reheating power of the building air-conditioning system*). During the cooling season, heat generated from luminaires and trapped in the room space is considered as the supplemental reheating energy that shall be deducted from the original reheating energy consumption with the only heat source of electric heating coil.

To approximate this energy-saving design in Energy Plus, the model classroom was added with two updated features. First, the harvested heat of the tested LED luminaires, which was otherwise trapped in the room space, was now removed. Second, the removed heat was counted into the reheating energy of the HVAC system. As a result, in Energy Plus simulation, both cooling load and reheating energy consumption could be reduced. Figure 33 is an illustration of common arrangement of the LED lighting fixture and HVAC air supply system for the energy-saving design. Figure 34 indicates how to utilize the portion of LED heat harvested in the room space as a supplemental reheating power to re-heat the discharged air in the conditioned room space.

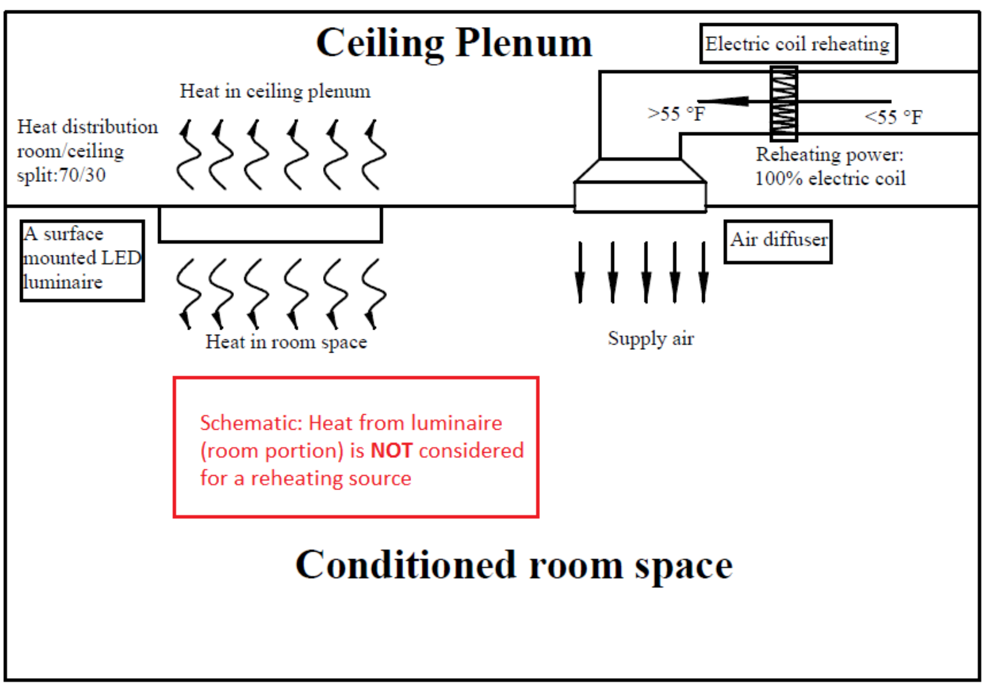


Figure 34 Common arrangement of the LED lighting fixture and HVAC air supply system

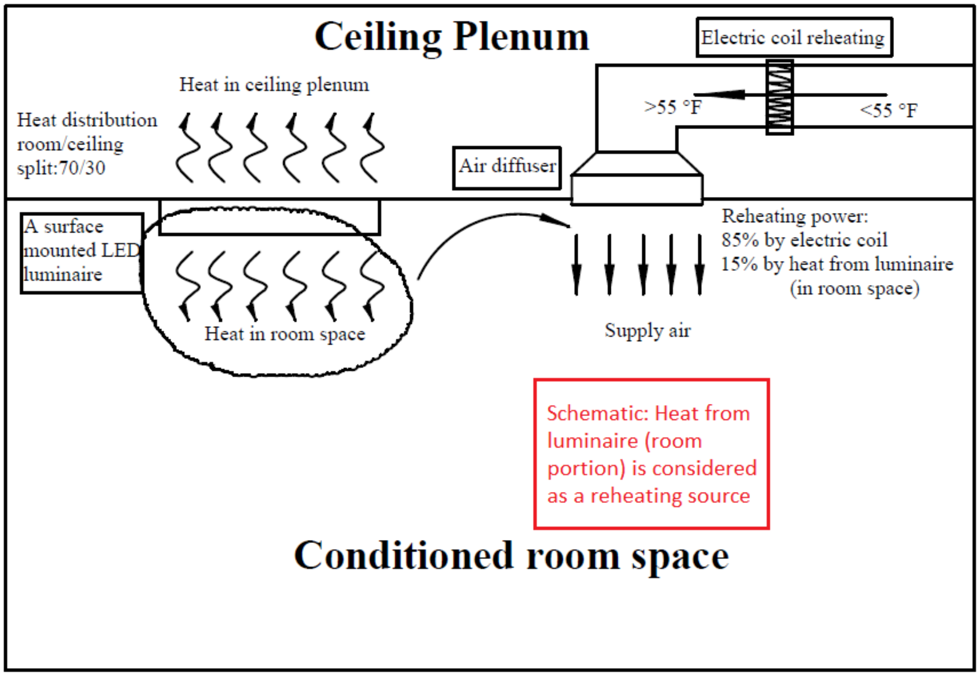


Figure 35 LED heat harvested in the room space as a supplemental reheating power to re-heat the discharged air in the conditioned room space

3.4.3 Energy Plus simulation results

In Energy Plus simulation, the input was the heat distribution pattern ('conditioned space/ceiling plenum split') of the tested LED luminaires obtained from the laboratory experiments in the Cold Room. The output was the building annual heating and cooling energy consumption for the primary school classroom equipped with each of the four different types of LED luminaires (ceiling-recessed or surfaced-mounted prototype LED fixtures, two off-the-shelf commercial LED fixtures), respectively. For comparison, results were obtained within/without deployment of the new energy-saving design. Tables 12 shows heating and cooling energy consumption of the typical primary school classroom with four different LED luminaires (two prototype LED and two off-shelf LED). Figure 36 illustrate heating, cooling and total energy of the classroom with four LEDs in graphic.

Table 12 Annual heating and cooling energy for the primary school classroom without deployment of the new lighting arrangement

Luminaire	**Ceiling recessed prototype LED**	**Surface mounted prototype LED**	**Ceiling recessed commercial LED**	**Surface mounted commercial LED**
Heating power per luminaire(W)*	50	50	50	50
Heat distribution (room/plenum split)	60.4/39.6	69.6/30.4	47.2/52.8	58.0/42.0
Annual **heating** energy (GJ)**	55.88	55.31	56.65	56.00
Annual **cooling** energy (GJ)	17.24	17.29	17.15	17.22
Annual **heating & cooling** energy (GJ)	73.12	72.60	73.80	73.22

*Heating power of four luminaires are assumed to be 50W in energy plus simulation.
**the annual heating energy contains energy consumption for space heating (in winter) and for reheating (in summer).

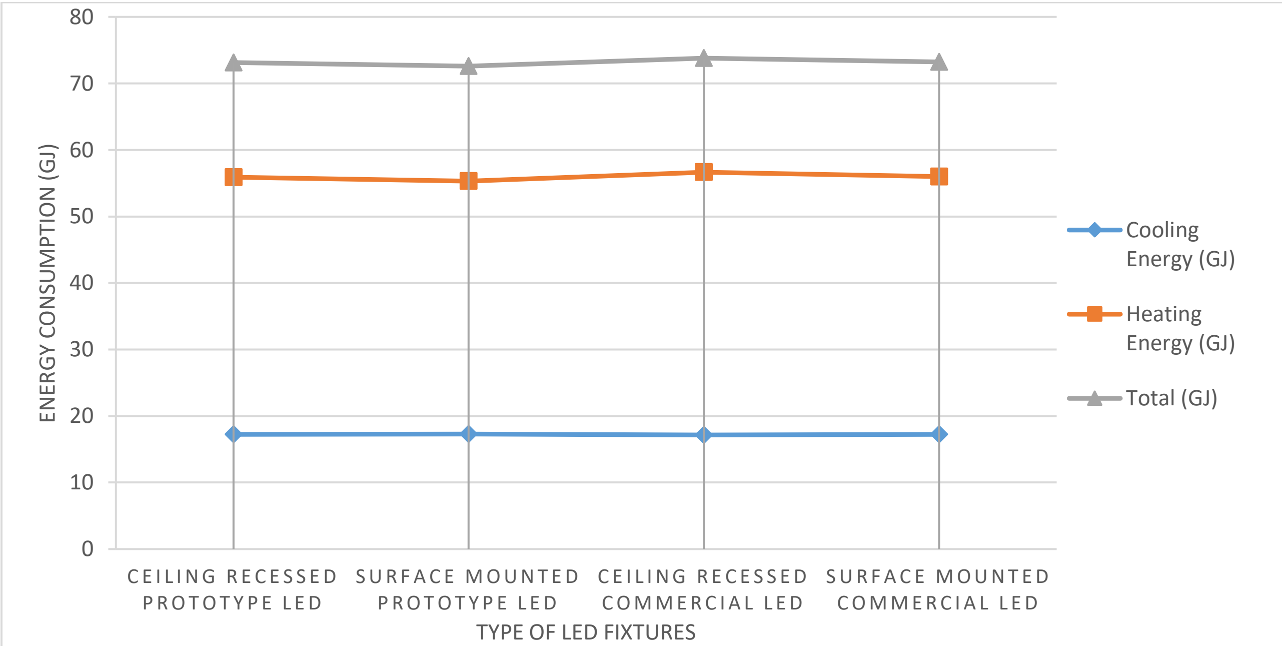


Figure 36 Summary of Energy Plus simulation

Table 13 shows the annual heating and cooling energy consumption of the primary school classroom with deployment of the new energy-saving design, which is only compatible with the prototype LED in this study. The surface mounted prototype LED luminaire trap 69.6% of heat in the room space, which is 9.2% more than the same LED with ceiling recessed mounting method (60.4% in room space). Therefore, this 9.2% more heat in the room space can be used for reheating in the summer and for heating in winter by using surface mounted but result a little bit higher cooling energy consumption in summer. As shown in Table 13 below, the new lighting arrangement is designed to utilize harvested LED heat in the room space, and therefore the reheating power reduced by 50% in theory (before deduction and after deduction in Table 13).

Table 13 heating and cooling energy of the classroom installed with the prototype LED fixture and with new lighting arrangement deployed

Luminaires	Ceiling recessed prototype LED	Surface mounted prototype LED
Heating power per luminaire(W)	50	50
Number of Luminaires in the 93.5m^2 Classroom	15	15
Heat distribution	60.4/39.6	69.6/30.4
Heating power in the room space (W/m^2)	4.92	6.00
Annual reheating energy (before deduction, in GJ)	4.93	4.70
Supplemental reheating energy (GJ)	2.47	2.68
Annual reheating energy (after deduction, in GJ)	2.46	2.02
Annual space heating energy (GJ)	50.95	50.61
Annual heating energy (GJ)	53.41	52.63
Annual cooling energy (GJ)	17.12	17.13
Annual heating and cooling energy (GJ)	70.53	69.76

CHAPTER 4

DATA ANALYSES AND RESULTS

Case 1 to Case 3 are designed to determine the relation between heating and cooling energy consumption and the heat distribution pattern (ceiling/room split) of LED luminaires. Case 4 shows how much energy can be saved by reducing reheat energy consumption, which enabled by the prototype LED with integrated lighting arrangement.

4.1 Case 1: the ceiling surface-mounted prototype LED luminaire vs. the ceiling-recessed prototype LED luminaire

Case 1 was the comparison of annual heating and cooling energy consumptions of the primary school classroom equipped with ceiling surface-mounted prototype LED luminaires vs. the ceiling recessed prototype LED luminaires. The results are shown in Table 14. Based on the laboratory test results, the ceiling recessed prototype LED luminaire could harvest 69.6% of its LED heat in the room space, which is 9.2% more than that when the same LED luminaire was surface mounted. In Energy Plus simulation, the primary school classroom equipped with surface-mounted prototype LED luminaires consumed 72.60 GJ of building heating and cooling energy for one-year period, which is 0.52GJ less than that with the surface mounted prototype LED luminaires.

Table 14 Energy consumptions simulated in Energy Plus of the primary school classroom equipped with surface mounted prototype vs. ceiling recessed prototype

Luminaire	Ceiling recessed prototype LED	Surface mounted prototype LED
Heating power of luminaire (W)	50	50
Heat distribution (room/ceiling split)	60.4/39.6	69.6/30.4
Annual **cooling energy** consumption of the primary school classroom (GJ)	17.24	17.29
Annual **heating energy** consumption of the primary school classroom (GJ)	55.88	55.31
Annual heating and cooling energy consumption (GJ)	73.12	72.60

4.2 Case 2: the ceiling recessed prototype LED luminaire vs. a ceiling recessed commercial LED luminaire

Case 2 was the comparison of annual heating and cooling energy consumptions of the primary school classroom equipped with the ceiling recessed prototype LED luminaire vs. a ceiling recessed commercial LED luminaire. The results are shown in Table 14. It was found that the ceiling recessed prototype LED luminaire with the new architecture of "Heat Arrangement of LED Arrays in Low Profile" could harvest more LED heat in the room space than the ceiling recessed commercial LED luminaire. Consequently, according to the Energy Plus simulation results with the heat distribution pattern ('conditioned space/ceiling plenum split') being the only variable, the primary school classroom installed with the ceiling recessed prototype LED luminaire (which harvest 60.4% LED heat in room space) consumes less heating and cooling energy per year than that with the ceiling recessed commercial LED luminaire (harvested 47.2% LED heat in room space).

Table 15 Ceiling recessed prototype vs. ceiling recessed commercial LED luminaire

Luminaire	**Ceiling recessed prototype LED**	**Ceiling recessed commercial LED**
Heating power of luminaire (W)	50	50
Heat distribution (room/ceiling split)	60.4/39.6	47.2/52.8
Annual **cooling energy** consumption of the primary school classroom (GJ)	17.24	17.15
Annual **heating energy** consumption of the primary school classroom (GJ)	55.88	56.65
Annual heating and cooling energy consumption (GJ)	73.12	73.80

4.3 Case 3: the surface mounted prototype LED luminaire vs. a surface mounted commercial LED luminaire

Case 3 was the comparison of annual heating and cooling energy consumptions of the primary school classroom equipped with the surface mounted prototype LED luminaire vs. a surface mounted commercial LED luminaire. The results are shown in Table 15. The surface mounted prototype LED luminaire with the new architecture design could harvest more LED heat in the room space than the surface mounted commercial LED luminaire. Consequently, according to the Energy Plus simulation results with heat the distribution pattern of 'conditioned space/ceiling plenum split' being the only variable, the primary school classroom installed with the surface mounted prototype LED luminaire (harvested 69.6% of LED heat in room space) consume less heating and cooling energy per year than that with the surface mounted commercial LED luminaire (harvested 58% of heat in room space).

Table 16 Surface mounted prototype vs. surface mounted commercial LED luminaire

Luminaire	**Surface mounted prototype LED**	**Surface mounted commercial LED**
Heating power of luminaire (W)	50	50
Heat distribution (room/ceiling split)	69.6/30.4	58.0/42.0
Annual **cooling energy** consumption of the primary school classroom (GJ)	17.29	17.22
Annual **heating energy** consumption of the primary school classroom (GJ)	55.31	56.00
Annual heating and cooling energy consumption (GJ)	72.60	73.22

4.4 Case 4: the ceiling recessed and surface mounted prototype LED with energy saving design and assumptions

Case 4 was designed to show how much energy can be saved by installing the new prototype LED luminaires with the new integrative lighting and heating arrangement. The results are shown in Tables 17 and 18. Table 16 is the comparison of energy consumptions between the surface-mounted new prototype LED luminaires with the energy saving design and the surface-mounted off-the-shelf LED luminaires. As shown in Table 17, compared to the annual heating and cooling energy consumption of the primary school classroom equipped with the surface mounted commercial LED luminaire, 4.7% of energy can be saved by replacing those luminaires with the new prototype LED luminaire.

Table 17 Energy consumption of the classroom equipped with **surface mounted prototype** LED with energy saving design vs. that of surface mounted commercial LED

Luminaire	**Surface mounted prototype LED**	**Surface mounted commercial LED**
Heating power of luminaire (W)	50	50
Energy saving technology	Utilizing room-portion heat as reheat power source	N.A.
Heat distribution (room/ceiling split)	69.6/30.4	58.0/42.0
Annual **cooling energy** consumption of the primary school classroom (GJ)	17.13	17.22
Annual **heating energy** consumption of the primary school classroom (GJ)	52.63	56.00
Annual heating and cooling energy consumption (GJ)	69.76	73.22

Table 18 shows the energy consumption of the ceiling surface-mounted prototype LED with the new energy saving design versus that of the conventional ceiling recessed LED. Assuming the heating power is 50W for both types of luminaires (under assumption#4), 4.4% annual heating and cooling energy could be saved in the primary school classroom equipped with the ceiling recessed prototype LED luminaires with “new lighting arrangement”, when compared to that of the same classroom equipped with the ceiling recessed commercial LED luminaires.

Table 18 Energy consumption of the classroom equipped with **ceiling recessed** prototype LED with energy saving design vs. that of ceiling recessed commercial LED

Luminaire	**Ceiling recessed prototype LED**	**Ceiling recessed commercial LED**
Heating power of luminaire (W)	50	50
Energy saving Technology	Utilizing room-portion heat as a supplemental reheat power source	N.A.
Heat distribution (room/ceiling split)	60.4/39.6	47.2/52.8
Annual **cooling energy** consumption of the primary school classroom (GJ)	17.12	17.15
Annual **heating energy** consumption of the primary school classroom (GJ)	53.41	56.65
Annual heating and cooling energy consumption (GJ)	70.53	73.80

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The goal of this study was to verify the new system architecture of "Heat Arrangement of LED Arrays in Low Profile" of future LED luminaires for reduction of building heating and cooling energy consumptions through integrative lighting and heating arrangement that interacts with the existing building HVAC system. This new system architecture of LED luminaire design enables more heat flux generated from the LED luminaires flowing forward to the conditioned room space while minimizing the portion trapped in the ceiling plenum. The portion of LED heat harvested in the room space can be utilized as supplemental space heating power in heating season (in most cases), and also as supplemental reheating power in cooling season.

The prototype LED luminaire with the new system architecture, which was either ceiling recessed or surface mounted, and two other off-the-shelf commercial LED luminaires (one ceiling recessed and one surface mounted) were tested in the calorimeter in the Cold Room to obtain their heat distribution pattern in terms of 'conditioned space/ceiling plenum split'. Based on the laboratory experiments in the Cold Room, among the tested samples of the LED luminaires, the new architecture of LED luminaire could help harvest more heat generated by LED chips in the room space than the other commercial LED luminaires do.

By analyzing Cases 1-3 in chapter 4, the following two statements can be concluded:

- Excluding the heat contribution from the LED driver, the prototype LED luminaire with surface mounted design can help harvest 9.2% more heat generated by LED chips in the room space than the same prototype luminaire with ceiling recessed design do (in Case 1).

- Compared with the heat distribution pattern of ‘conditioned space/ceiling plenum split’ of the two off-the-shelf LED luminaires bought from market, the new integrative architecture of LED luminaire can help harvest more heat generated by LED chips in the room space (in Case 2 and Case 3).

The annual heating and cooling energy consumption of a typical primary school classroom equipped with those tested LED luminaires were simulated in Energy Plus with details specified such as located in climate zone 4 (Lawrence, KS), single floor classroom with flat room and electric heating and cooling system, etc. Therefore, the results obtained in Energy Plus simulation in this study are all subject to those preconditions. By analyzing the heat distribution of LED luminaires and the simulation results of annual heating and cooling energy consumptions of the modeled primary school classroom with different LED luminaires installed in case 1 through case 3, two conclusions can be drawn as follows:

- With the assumption #4 that each LED fixtures are assigned with the same total heating power in Energy Plus, higher percentage of heat harvested in the conditioned room space can reduce annual heating and cooling energy consumption of the primary school classroom.
- Higher percentage of heat harvested in the conditioned room space results in higher annual cooling energy consumption and lower annual heating energy consumption. With the harvested heating power of LED luminaire increased in the room space, the amount of energy saved in the space heating is larger than that of energy wasted in the space cooling.

Case 4 shows that the amount of energy saved by implementation of the integrated lighting and heating arrangement with the new prototype LED luminaires in the primary school classroom, by comparing to the same configurations without the new integrated lighting arrangement. By comparing the simulation results in Energy Plus of the primary school classroom installed with prototype LED luminaires (ceiling recessed and surface mounted) under the conditions described in assumption #3 (the prototype LED fixture with new lighting arrangement enable the heat generated by LEDs and harvested in room space can be utilizing as reheating power in cooling season) to that of the same space installed with current commercial LED luminaires (ceiling recessed and surface mounted), following conclusions can be drawn:

- The primary school classroom equipped with the new type of LED luminaires with integrative lighting and heating arrangement can reduce energy consumption for space heating, space cooling and reheating.
- The implementation of the integrative lighting and heating arrangement in the primary school classroom equipped with the ceiling-recessed prototype LED luminaires can save 4.7% of annual heating and cooling energy, compared to the energy consumptions of the same classroom installed with two commercial ceiling-recessed LED luminaire without adoption of the integrative lighting and heating arrangement. The savings lowered to 4.4% when compared to surface-mounted off-the-shelf LED luminaires.

5.2 Discussion

Since the heat distribution pattern (‘conditioned space/ceiling plenum split’) of LED luminaires affects building heating and cooling energy consumption, the luminaire form factor and its installation method become important in the development of future solid-state lighting luminaires. LED luminaires of next generation, which deploy the system architecture of “Heat Arrangement of LED Arrays in Low Profile” and the integrative lighting and heating arrangement with the existing HVAC system, may have most energy savings for space heating in winter and assisting the reheat coil of the HVAC system for reheating the discharged cool air in summer. How much cost reduction by using the new LED technologies may be estimated by the amount of energy saved (in GJ) and local electricity price ($/kWh). On the other hand, both space heating and reheating could also use natural gas, which could be much cheaper than electricity. As a result, further investigation on the life cycle cost effectiveness of the integrative LED lighting and heating technologies is necessary.

Moreover, the heat gain from LED driver could be harvested together with the LED luminaire, which was not examined in the present study. In a typical case, a 25 Watts output LED driver may generate approximately 3 Watts heating power, which takes 12% of its power output of the LED driver. Therefore, installation of LED drivers (e.g. attached or remote mounted; on the back or inside of luminaire’s housing) and its location (above or below the ceiling) could affect the heat distribution of a LED luminaire. Different LED drivers with different sizes and thermal specifications (heating power per unit output power) will surely change the total heating power of a LED luminaire.

Additionally, DOE (U.S. DoE, 2008, *Figure 10*) claimed at least 20% of energy consumption of LED luminaires is converted to radiant energy (visible light and radiation).

Therefore, the radiation/convection split, which was not measured in the present study, could influence the calculation of internal heat gains and finally affect building annual heating and cooling energy consumption. The radiation/convection split of LED luminaires is thus recommended to be measured in future studies, especially those studies on thermal interactions between new types of LED luminaires with integrative lighting and heating arrangement and conditioned supply air of the HVAC system.

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Appendix

Calculation sheet of the heating power of the tested LED luminaires in the Calorimeter

Test Case	Mounting Method	Relative Humidity (%)	Absolute Humidity	Barometric Pressure (kPa)	Air Speed (m/s)	Volume Flow (m3/s)	Mass Flow (kg/s)	Cavity in Calorimeter	Heating Power (kW)	Heating Power (W)	Temperature of air intake (°C)	Temprature difference (°C)	Temperature of air exhaust (°C)
		Read from humidity sensor	Calculated	Obtained from weather station	Read from Fan Sensors	Calculated	Calculated	Ceiling or Room	Calculated	Calculated	Read from temperature sensors	Calculated	Read from temperature sensors
1	CEL-RESD	0.600	0.0117	102.6102	1.64	0.01264	0.014897	CEILING	0.009169	9.17	24.10	0.60	24.70
	CEL-RESD	0.587	0.0115	102.6102	1.64	0.01264	0.014903	ROOM	0.012225	12.22	24.07	0.80	24.87
2	CEL-RESD	0.681	0.0136	100.9147	1.70	0.013102	0.015142	CEILING	0.01168	11.68	24.10	0.75	24.85
	CEL-RESD	0.666	0.0133	100.9147	1.70	0.013102	0.01515	ROOM	0.015056	15.06	24.05	0.97	25.02
3	CEL-RESD	0.634	0.0126	100.9147	1.70	0.013102	0.015165	CEILING	0.027214	27.21	24.39	1.75	26.13
	CEL-RESD	0.625	0.0125	100.9147	1.70	0.013102	0.01517	ROOM	0.027213	27.21	24.39	1.75	26.13
4	CEL-RESD	0.661	0.0132	100.9147	1.60	0.012331	0.014261	CEILING	0.022776	22.78	24.58	1.55	26.13
	CEL-RESD	0.648	0.0129	100.9147	1.60	0.012331	0.014267	ROOM	0.024885	24.88	24.41	1.70	26.11
5	CEL-RESD	0.586	0.0115	101.9306	1.54	0.011869	0.0139	CEILING	0.025878	25.88	24.87	1.82	26.69
	CEL-RESD	0.568	0.0112	101.9306	1.54	0.011869	0.013908	ROOM	0.023905	23.91	24.82	1.68	26.50
6	SUR-MONT	0.699	0.0138	101.9310	1.47	0.011329	0.013221	CEILING	0.022163	22.16	25.02	1.63	26.64
	SUR-MONT	0.648	0.0128	101.9310	1.47	0.011329	0.013242	ROOM	0.033808	33.81	25.02	2.48	27.50
7	SUR-MONT	0.678	0.0134	101.9310	2.00	0.015414	0.017999	CEILING	0.016112	16.11	24.01	0.87	24.88
	SUR-MONT	0.634	0.0125	101.9310	2.00	0.015414	0.018025	ROOM	0.029996	30.00	23.91	1.62	25.53
8	SUR-MONT	0.568	0.0112	101.5920	1.80	0.013873	0.016201	CEILING	0.016521	16.52	24.07	1.00	25.07
	SUR-MONT	0.526	0.0104	101.5920	1.80	0.013873	0.016223	ROOM	0.0294	29.40	24.07	1.77	25.84
9	SUR-MONT	0.557	0.0110	101.5920	1.76	0.013564	0.015847	CEILING	0.02091	20.91	24.24	1.29	25.53
	SUR-MONT	0.515	0.0102	101.5920	1.76	0.013564	0.015868	ROOM	0.032137	32.14	24.24	1.98	26.22
10	SUR-MONT	0.647	0.0128	101.5920	1.68	0.012948	0.015083	CEILING	0.01958	19.58	24.80	1.26	26.06
	SUR-MONT	0.600	0.0119	101.5920	1.68	0.012948	0.015106	ROOM	0.02979	29.79	24.80	1.92	26.72