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EVALUATION OF AN EXTENDED-DUCT AIR DELIVERY SYSTEM IN TALL SPACES CONDITIONED BY ROOFTOP UNITS

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ABSTRACT

Mixing ventilation in high bay buildings conditioned by rooftop units involves supplying and returning air near the ceiling. Several problems occur in tall spaces, such as higher return air temperatures in the summer and excessive stratification in the winter. A novel air delivery strategy is investigated that involves supplying and returning air at different heights depending on the season. In the summer, air is supplied low and returned just above the occupied zone in order to cool the occupied zone directly, letting the upper zone stratify. In the winter, air is supplied high and returned low in order to draw warm air down from the ceiling, thus promoting destratification. This system's performance was investigated in a full-scale experiment using measured temperature profiles and utility bills. A calibrated EnergyPlus model used measured temperature profiles as an input to a room-air model to study the effects of stratification on building energy consumption. The EnergyPlus model predicts 19% yearly HVAC electricity savings when considering the additional pressure drop of extended ducting and 37% yearly HVAC electricity savings without considering extra pressure drop. A utility bill analysis of the test facility shows a yearly 28.8% reduction in HVAC electricity consumption.

INTRODUCTION

Commercial buildings accounted for 18% of the total U.S. energy consumption in 2014 (EIA, 2015). Of this energy consumption, space heating constitutes 22.5% and space cooling constitutes 14.8%. From 2003 to 2012, the number of commercial buildings increased by 14% and the floor space of commercial buildings increased by 21%. An increase in the number and size of commercial buildings calls for more efficient building energy use. Numerous strategies exist for conserving building HVAC energy, such as more efficient primary systems, controls, and improvements to the building envelope.

Control over indoor air distribution is another possible way to save HVAC energy. Air distribution has been researched for roughly the past 35 years, focusing particularly on underfloor air distribution (UFAD) and displacement ventilation (DV). These strategies utilize low velocity supply air diffusers near the floor to provide cooling to the occupied zone. Although large differences between simulated and measured energy savings are reported in the literature, some researchers claim that UFAD saves 30% cooling energy, particularly in spaces with tall ceilings [1]. However, these air distribution strategies do not lend themselves easily to the retrofit of existing overhead, mixing ventilation systems because they require different supply air conditions than traditional, packaged heating and cooling systems are designed to provide.

A new system has been tested that involves extending ducts to supply and return air at different locations in the space, as shown in Figure 1 for cooling and heating mode. In cooling season, air is supplied near the floor and returned above the occupied zone. The goal is to cool the occupied zone directly, letting the upper zone stratify. Benefits in cooling mode include raising the space's average temperature (which reduces heat gain through the building envelope), decreasing the temperature in the occupied zone relative to the mean air temperature (which makes for easier-to-reach setpoints), and decreasing return air temperatures (which decreases the cooling load).

In heating season, air is supplied near the ceiling and returned near the floor. The goal is to promote mixing by 'drawing down' the warm air from the ceiling. Benefits in heating mode include easier-to-reach setpoints due to decreased stratification. This could save energy by decreasing the run-time of fans.

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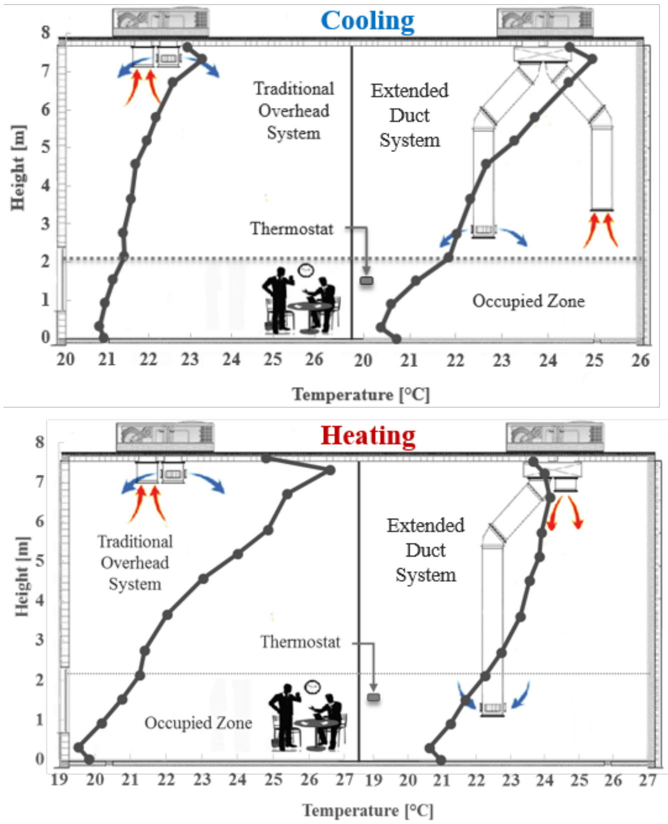

Figure 1: Measured temperature profiles under baseline (left) and retrofit (right) duct configurations

LITERATURE REVIEW

Singh and Olivieri tested an air delivery strategy that retrofits the overhead system to supply and return air near the floor [2]. Their idea to change the supply and return duct location stems from a desire to "eliminate either the effect of the induction of the upper level hot air into the supply air stream or the pulling down of the upper level hot air by the return air or both". Through a series of ten tests, they reduced the height of supply and return ducts from ceiling-level to floor-level. The authors showed that supplying air in the bottom third of the room gives the most stratification and lowest occupied zone temperature. The return duct height has little effect on stratification, though they do not test low-level supply and high-level return. In a full-scale experiment with a well-controlled baseline, the combination of floor-level supply and return saved 33-50% depending on ambient temperature and solar heat gain.

Said et al. [3] studied the effects of thermal stratification in large aircraft hangars during heating season. The heating system was the overhead down-draft air delivery system. Temperatures were averaged over long measurement periods, giving stratification ranging from 4 K to 11 K. Two distinct, linear gradients are observed – one below 2 m and one above. Outdoor temperature and ceiling fans are shown to have little effect on stratification. BLAST simulations estimate a 38% gas use reduction when the stratification is reduced from 8K to fully mixed (0 K).

Previously, researchers could include vertical temperature profiles in a building simulation by splitting a single room vertically into multiple zones. This is the procedure used by Said et al., above [3]. However, EnergyPlus now includes several room air models, such as the non-dimensional height, displacement ventilation, and underfloor air distribution models. Pan et al. used the non-dimensional height model to study atriums that were 80-130 m tall [4]. Using temperature profiles generated from their CFD model, they show that the mixing model over-predicts the cooling load by 88-212% compared to the room air model.

ROOM AIR MODELING

Figure 2 shows one example of a non-dimensional height room air object. The vertical height is non-dimensionalized such that 0 represents the floor and 1 represents the ceiling. Temperatures are a function of height, where each height is called a node. At every node, the user inputs the difference between the node temperature and the room mean air temperature. The exhaust and return duct temperature offsets from mean air temperature can be input as well. All node temperatures and offset temperatures are fixed relative to the room's mean air temperature. The mean air temperature is calculated each timestep in the EnergyPlus heat balance equations.

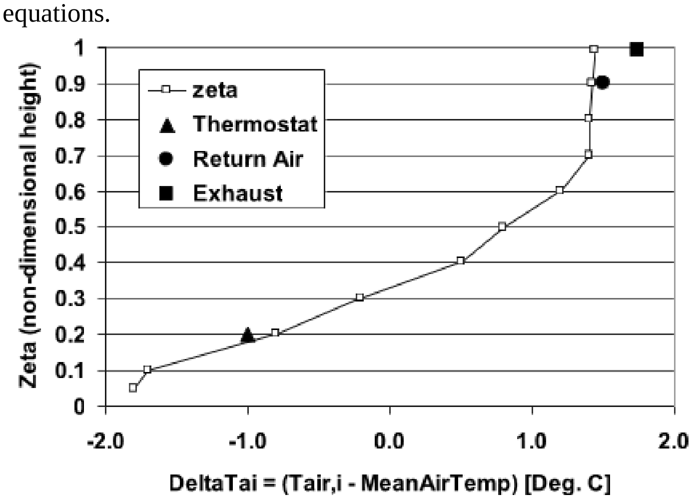

Figure 2: Non-dimensional height room air model [5]

Although there exists an input for thermostat offset temperature, it is was found to not currently be used for anything other than reporting of an output variable, *ZoneThermostatAirTemperature.* The implementation of the non-dimensional height room air model in EnergyPlus is based on Griffith and Chen [5]. However, EnergyPlus modified the original implementation to make the software more general [6]. A brief description of Griffith and Chen's procedure is provided here. A simple method is proposed to include their treatment of

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thermostat offset temperature using the current EnergyPlus implementation.

Room air modeling involves altering the inside surface heat balance equations to include temperature gradients. The software maps each surface to a corresponding node to obtain its heat transfer coefficient. Then, the rest of the heat balance system is solved, the zone mean air temperature is updated (remember, the temperature profile is fixed about the mean air temperature), and the program moves to the next timestep. The return air offset directly changes the temperature of the return air. Both of these aspects are implemented in the original paper by Griffith and Chen and in EnergyPlus.

EnergyPlus controls the room such that the zone mean air temperature is equal to the thermostat setpoint. In the original paper, however, the zone is controlled such that the temperature sensed by a hypothetical thermostat is equal to the thermostat setpoint. In keeping with Griffith and Chen's notation, define:

$T_{setpoint}$ Input set point temperature
T_{stat} Temperature measured by the thermostat

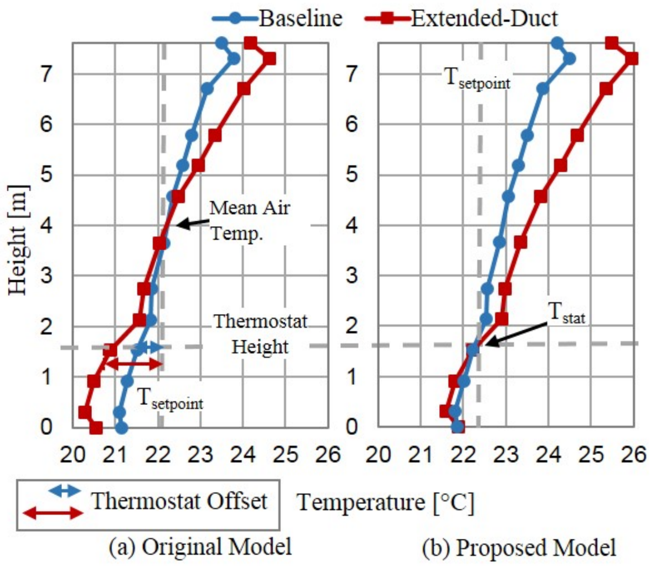

Figure 3: Temperature profile before (a) and after (b) accounting for thermostat offset

Since the mean air temperature occurs higher than the thermostat is located, the temperature profile is shifted left by the amount given by the red and blue arrows in Figure 3(a). To produce the measured temperature profiles shown in Figure 3(b), the thermostat setpoint has to be raised in the model by the amount given by the arrows. For example, the retrofit saw an offset of 1.2 K between the mean air temperature and the temperature at the height of the thermostat. Therefore, the input setpoint to EnergyPlus will be the actual building's setpoint, 22.2°C, plus 1.2°C. Therefore, the thermostat setpoint in the model is 23.4°C. In this manner, the model artificially controls the zone to the same thermostat setpoint as the real building and maintains the correct temperature profile about the mean air temperature.

TEST FACILITY

A 7000 m^2 manufacturing plant has allowed measurements of the extended-duct system to be taken for one year. Vertical temperature profiles have been measured from January 2015 – March 2016. Utility bills have been collected for January 2014 – March 2016. The test facility has installed four energy saving retrofits in 2015: upgrading from metal halide lights to LED lights, upgrading to higher SEER RTUs, installing the extended-duct system, and installing a more efficient industrial air compressor. A layout of the test facility is shown in Figure 4. The extended-duct system was installed in both manufacturing rooms and the storage room. The RTUs in these rooms were on the same electrical panel, so their lump electricity consumption was metered.

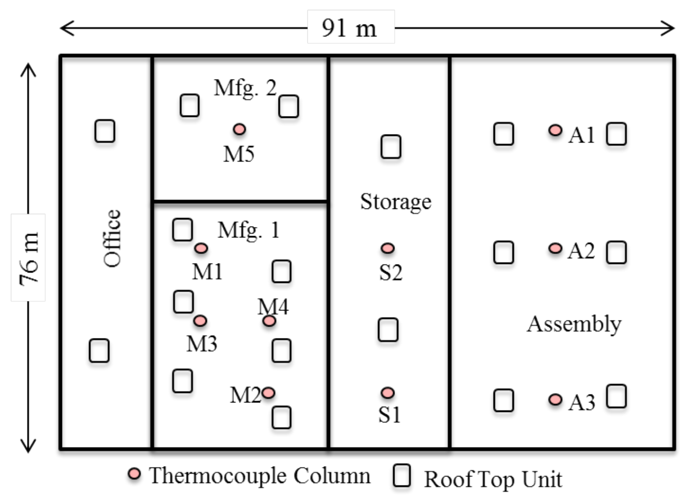

Figure 4: Test facility layout and measurement locations

Each of the 10 thermocouple columns contains 13 thermocouples – one measuring floor surface temperature, one measuring ceiling surface temperature, and 11 measuring air temperature from floor to ceiling. The sampling rate is 20 s and the thermocouple uncertainty is 0.5°C. Each column has a data acquisition module that communicates with a central computer via Wi-Fi. The test facility is located next to Baltimore Washington International Airport, which makes for convenient access to accurate weather data.

BUILDING ENERGY SIMULATION DEVELOPMENT AND CALIBRATION

A five zone EnergyPlus model was created based on numerous site visits. Most aspects of the building were known accurately, such as schedules (loads, occupancy, setpoints), lighting density, constructions (floor, walls, ceiling), RTU specifications, and outdoor weather. Infiltration was assumed to be 0.001024 m^3/s per square meter of exterior surface area based on a PNNL report [7]. The economizers used differential enthalpy control with a minimum outdoor air ratio of 10%. However, it was found that the economizer dampers were malfunctioning for the first half of 2015. In the original model, large differences were observed between simulated and

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measured gas consumption for this reason. Therefore, the economizers were set to use constant 10% outdoor air, except for the office which uses normal 10-100% outdoor air depending on differential enthalpy control.

Plug load density is difficult to determine for the manufacturing rooms because the CNC machines consume a lot of power at almost any part load ratio. Since plug load density varies significantly and can reasonably assume a wide range of values, it was varied during calibration. It was found that 35-45 W/m^2 produced accurate results for the electricity in the winter, spring, and fall. During summer, the plug loads were reduced to half their usual peak value, except in the office.

Gas is used only for space heating. The offices have VAV terminal units with electric reheat of unknown capacity. Gas use predictions were within 5% of measured values for winter and summer months. However, gas use was under-predicted by up to 35% in April and May and over-predicted by 93% in October. Electricity was calibrated to within the specifications given by ASHRAE Guideline 14. Based on Table 1, this model is not considered calibrated for gas because the CV(RSME) is not less than 15%. CV(RSME) characterizes the closeness of the simulation to measured data. NMBE characterizes whether the simulation 'over-predicts' or 'under-predicts' the measured data. More accurate simulations will produce smaller CV(RSME) and NMBE absolute values.

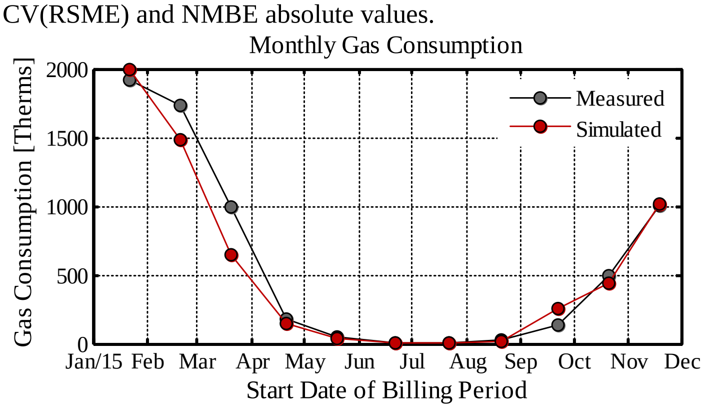

Figure 5: EnergyPlus model gas calibration

Table 1: ASHRAE Guideline 14 statistics

		NMBE [%]	CV(RSME) [%]
Electricity	Daily	-0.27	7.75
	Monthly	1.74	5.01
Gas	Monthly	2.04	22.84
Target	Hourly	< 10	< 30
	Monthly	< 5	< 15

The four retrofits (lights, RTUs, extended-ducting, compressor) were implemented in a model for 2015 using schedules to turn certain retrofits "on" and "off" when they were installed.

RESULTS AND DISCUSSION

Utility Bill Analysis

Based on Table 2, the facility saved an average of 16.3% electricity in 2015 through four retrofits. It was attempted to normalize energy use by degree days, as shown in Figure 6. Building electricity consumption does not correlate with cooling degree days ($R^2 = 0.019$). The poor correlation between net facility electricity consumption and degree days indicates that the building is not sensitive to external heat loads and is instead dominated by internal heat loads. Gas consumption correlates very well with heating degree days ($R^2 = 0.97$). Since gas consumption correlates with ambient temperature, it was attempted to calculate energy savings in terms of therms-per-degree-day. Since the other retrofits, particularly the lighting and compressor upgrades, removed a significant portion of the heat generated in the space, the building will compensate by using more gas. Therefore, this amount of heat has to be added back for a fair comparison. This amount of heat is not accurately known, especially for billing periods when the facility is not in heating mode the entire time. Furthermore, only two billing periods are available for the period after the extended-duct system was changed to heating mode. Due to the influence of the other retrofits and the limited number of post-retrofit data points, the utility bill analysis is inconclusive for heating season.

Table 2: Utility bill analysis for net site electricity

Electricity Consumption [MWh]				
Month	**2014**	**2015**	**Retrofit Installation**	**Reduction**
Jan	177.7	173.6	-	2.3%
Feb	159.7	165.3	-	-3.6%
Mar	152.3	130.8	Lighting	14.1%
Apr	166.9	137.4	-	17.7%
May	158.3	125.9	-	20.5%
Jun	165.2	145.9	RTUs	11.7%
Jul	176.2	122.3	Ducting	30.6%
Aug	166.1	125.7	-	24.3%
Sep	168.6	137.5	-	18.5%
Oct	157.6	117.7	Compressor	25.3%
Nov	123.3	113.0	-	8.3%
Dec	148.1	112.4	-	24.1%
Total	1919.8	1607.5	-	16.3%

Measured Temperature Profile

Temperatures were averaged by season and again by room, shown in Figure 7. The closed markers correspond to the baseline period, January 2015 – July 2015. The filled markers correspond to the period after the extended duct system was installed, July 2015 – February 2016.

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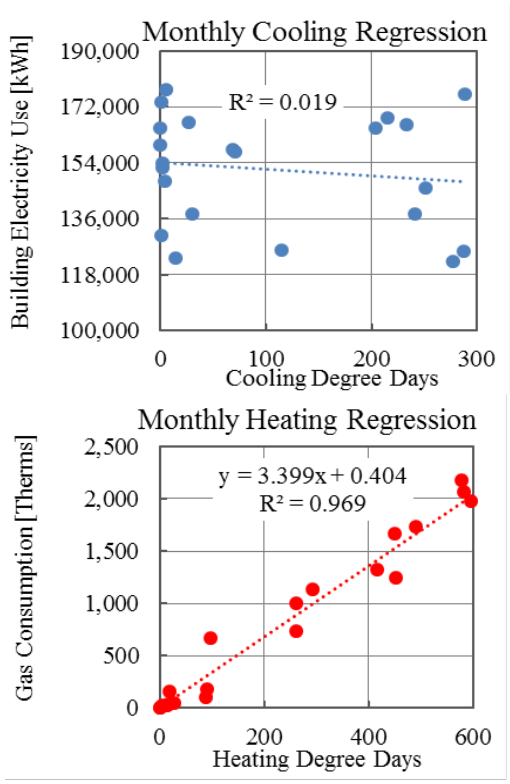

Figure 6: Degree day normalization for monthly data

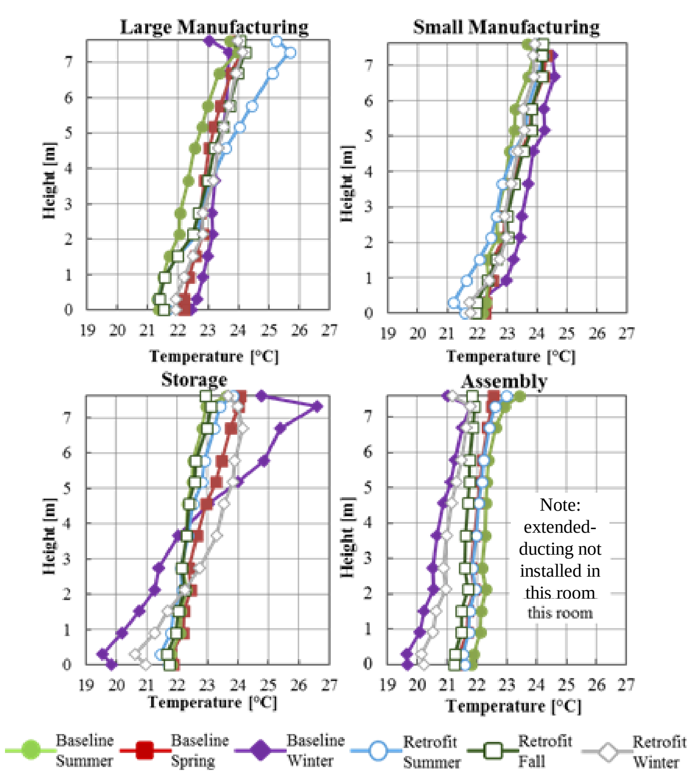

Figure 7: Measured temperatures averaged by season and room

In the large manufacturing room, the room with the greatest cooling load, stratification increases slightly in winter and spring/fall because this room is in cooling even into parts of winter. In summer, the temperature in the occupied zone remains the same, but stratification in the upper portion of the space increases by 1.7 K. The same level of stratification is observed in the small manufacturing room during summer, however the occupied zone is colder during the retrofit period than the baseline period because the measurement column was close to the supply air diffuser.

In the storage room, 7.1 K stratification was measured in the baseline winter period; the largest stratification seen at the test facility. This room has few heat sources (lights and occupants) and a higher infiltration rate due to two bay doors on the south wall. The extended-duct retrofit reduced the stratification to 3.5 K. Similarly, a slight reduction in stratification, 0.7 K, was observed in spring/fall because this room was predominantly in heating. In summer, stratification increased 0.8 K.

The assembly room did not have the extended-duct system installed. The plot is shown in Figure 7 to act as a 'baseline' room. It illustrates that different possible conditions between the baseline and retrofit periods, such as weather, plug-loads, or building use, do not exist or do not impact the temperature profiles seen in the facility.

These exact 24 temperature profiles were input to EnergyPlus for their corresponding room and season. For each profile, the mean air temperature was computed, then 11 nodes were used to specify the temperature profile about this mean air temperature. The floor and ceiling surface temperature was not input because there is no available way to do so. Mixing ventilation was assumed for the office.

Building Energy Simulation

Two models were created based on the calibrated 2015 model – one with all measured baseline temperature profiles and one with all measured extended-duct (retrofit) temperature profiles. The set point offset was also changed to correspond with the appropriate temperature profiles. The temperature profile used for each time period in each model is shown in Table 3. The names of the temperature profiles correspond to the legend in Figure 7.

Table 3: Temperature profiles corresponding to EnergyPlus models

Period	Mixing ventilation model	Extended-duct model
01/01 – 03/23	Baseline Winter	Retrofit Winter
03/24 – 05/31	Baseline Spring	Retrofit Fall
06/01 – 09/22	Baseline Summer	Retrofit Summer
09/23 – 11/31	Baseline Spring	Retrofit Fall
12/01 – 12/31	Baseline Winter	Retrofit Winter

The extended-duct system adds air pressure drop through longer ducts and more 90 degree elbows. Although the elbows are vaned, the loss coefficient is still 0.33. The fan static

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pressure rise for the baseline fan has been calculated to be 144.5 Pa. Assuming four extra elbows and 6 m extended ducting, the pressure rise for the extended-duct system is 248.4 Pa. It was of interest to compare the energy savings of the real system with extra pressure drop with the energy savings of a well-designed system without extra pressure drop. The calculated HVAC energy savings of the extended-duct system over an entire year are shown in Table 4.

Table 4: Simulated energy savings due to the extended-duct system

Model	Description	HVAC Electricity Savings [%]	Facility Electricity Savings [%]	Gas Savings [%]
1	Same pressure drop	37.4	5.0	7.7
2	Extra pressure drop	19.3	2.2	25.2*

*extra pressure drop increases fan heat gains, which offsets the heating load

When fan power consumption is the same in baseline and extended-duct models, stratification alone saves 37.4% electricity and 7.7% gas. In other words, these savings are realized by the room air modeling temperature profiles, return air offset, and thermostat offset. When factoring fan pressure drop into the model, the savings dropped to 19.3% electricity. The gas savings increased because the added heat of the fans required less gas to be burned and should therefore not be considered a benefit. As a percentage of the total facility electricity (i.e. not just HVAC energy), Model 1 shows a 5.0% electricity savings and Model 2 shows a 2.2% electricity savings.

CONCLUSIONS

A full-scale experiment was conducted in a high-bay test facility to measure the effects of a new air delivery strategy. The experimental study shows that, in cooling, supplying and returning air directly to the occupied zone produces an acceptable temperature gradient in the occupied zone, while increasing stratification in the upper portion of the space. In heating, supplying air from the ceiling vertically downward while returning air in the occupied zone has the potential to reduce stratification, though not eliminate it entirely. In both heating and cooling, the effects of the installed system are more pronounced in rooms that have high cooling and heating loads.

Building energy simulation is used to show how stratification influences a building's energy use. A novel approach used room air modeling with 24 measured temperature profiles over one year to capture the effects of return air temperature offset, thermostat offset, and stratification. It was found that increased fan energy consumption due to the XChanger system's larger pressure drop can depreciate the energy savings by 50%.

Based on the utility bill analysis, XChanger saves the facility 28.8% HVAC electricity over the course of one year. The building energy simulation results bracket this result – stratification alone resulted in 37.4% HVAC electricity savings while accounting for pressure drop resulted in 19.3% HVAC electricity savings. Building energy simulation shows that the extended-duct system saves 7.7 – 25.2% gas, depending on fan power consumption.

NOMENCLATURE

CNC	Computer numerical control
CV(RSME)	Coefficient of variation of the root mean squared error
LED	Light emitting diode
NMBE	Normalized mean bias error
RTU	Rooftop unit
SEER	Seasonal energy efficiency ratio
VAV	Variable-air-volume

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