TEMPERATURE PROFILES AND WINTER DESTRATIFICATION ENERGY SAVINGS

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Introduction

In recent years there has been increased interest in destratification as a means to improving heating efficiency. What is needed is a relatively simple method that can produce estimates within 10% of measured reductions in heating load using readily available data. An estimate of the cost of installing and operating the fans to de-stratify the air is also needed in order to assess the cost benefit.

The simplest contemporary method for estimating winter energy savings from destratification focuses on the difference in air temperature between floor level and underside of roof. For large single storey buildings with roof heights around 9m, such as shipping and receiving warehouses, stratification can be significant with temperature differences between floor level and underside of the roof between 17 K to 20 K. With high air temperatures under the roof, the roof surface typically offers the largest surface for heat loss. It is assumed that after destratification, the air is well mixed by large ceiling fans so that the average temperature of indoor air at various heights above floor level is more uniform. To estimate energy savings from forced air furnaces, the difference between heat lost through the roof at the two temperature differences, before and after destratification, is calculated.

Heat loss by conduction through the walls is relatively constant. Heat transfer through the roof can vary significantly. In winter, this is due mainly to the effects of wind, and radiant heat exchange with the sky. In order to calculate the heat flow through the roof a U value for the roof is estimated. It is often difficult to assign a reliable value for the thermal conductivity for envelope elements in existing buildings. Detailed construction drawings or specifications are rarely available, and even if they are, they do not necessarily represent how the building was actually built. Older insulation can be compromised by absorption of moisture.

The simplest contemporary method also ignores the influence of infiltration and ventilation. Heat losses due to ventilation and infiltration can amount to 20% to 50% of the total heat loss from a building. Not accounting for this heat loss due to ventilation in estimating energy savings from destratification can lead to significant errors. This method also ignores the contribution of heat from sources in the space such as lighting, people and machinery. More complex methods attempt to account for these influences.

Keywords: destratification, energy efficiency, heating

A better approach to estimating destratification savings

There is a better way to estimate winter heating savings due to destratification. Occupants of existing buildings usually have well documented data on the amount of heating fuel used during a heating season from their utility company invoices. These invoices also often have the degree days of heating associated with each billing period. If heating degree data is not provided on invoices, it can be obtained from local climate records along with the average outdoor air temperature during a particular period of time. These data can be used to calculate the overall rate of heat loss through the building envelope over a given period and compare it with previous heating seasons.

Take for example a 5388 m^2 shipping and receiving warehouse in Middletown in the State of New York. During a monitored period of 89 days, the total heating degree days were 1233 over a base of 18.3°C, and the average outdoor air temperature was 5°C. For more information on degree days see chapter 29 of the 2001 ASHRAE Handbook of Fundamentals. The indoor thermostat temperature near floor level was maintained at 18.3°C. Before destratification the air temperature at the underside of the roof deck, 8.99m above floor level, was 31.7°C. The flat roof consisting of bar joists, metal decking, polyiso insulation (tapered for fall to drains) and single ply membrane was estimated to have an average heat transfer coefficient of 0.738 W/m^2.K. Natural gas energy consumed by the forced-air furnaces, mounted 6.4 m above the floor, over an 89 day period from February through April, 2003 was 2654 GJ. Large ceiling fans used for destratification circulate the entire volume of indoor air between 0.3 and 1.0 times per hour with local air velocity kept below 0.2 m/s to avoid drafts.

The amount of heat released inside the building from sources other than the furnaces was estimated using data collected on site and methods provided in Chapter 29 of the 2001 ASHRAE Handbook of Fundamentals. These other sources of heat can be important. During the warmer winter months, if the thermostat setting is maintained, heat from sources other than the furnaces will provide an increasing proportion of heating to the building. Aggregating the typical quantities of heat released from lighting 39 kW, people 1.3 kW, and machinery, 13.5 kW in shipping and receiving warehouses from the estimates above gives a total of approximately 54 kW. This is equivalent to 10 W/m^2 based on floor area of the building.

In the method proposed by Pignet and Saxena, (2002), the estimated average indoor air temperature of stratified air assumes a linear vertical profile between floor and underside of the roof. In this case, the average air temperature after thorough mixing would be (31.7 + 18.3) / 2 or 25.0°C.

The average seasonal rate of heat loss UA through the building envelope in W/K, before destratification can be calculated using Equation 1.

$$UA = H / LTMTD \quad W/K \qquad \text{(eq. 1)}$$

Where

H = average rate of heat loss through the entire building envelope (W)

U = average heat transfer coefficient for the entire building envelope (W/m^2.K)

A = surface area of the element (m^2)

LTMTD = long term mean temperature difference (K) (indoor and outdoor air)

(5°C is the average outdoor air temperature for the sample heating season.)

The heating energy provided by the furnace in Watts during the sample heating season is 20,617 GJ, times the efficiency of the furnace (0.7) divided by the duration of the heating season in seconds. This is equal to around 170,445 W.

Heat from other sources in the warehouse during the sample heating season is the heat release rate 10.0 W/m^2 times the floor area of the warehouse, 5388 m^2. This equals 53,880 W giving a total heat loss of 224,325 W. Using equation 1

$$UA = (224{,}325) / (25 - 5)$$

$$= 11{,}216 \text{ W/K}$$

The reduced heat load, RHL, due to destratification is calculated using Equation 2.

$$RHL = (UA) \times (IATB - IATD) \qquad \text{(eq. 2)}$$

$$= 11{,}216 \times (25 - 18.3)$$

$$= 75{,}147 \text{ W}$$

Where

RHL = reduced heating load due to destratification (W)

UA = lumped time averaged rate of heat loss for the building envelope per K of indoor/outdoor season average temperature difference (W/K)

IATB = average indoor air temperature before destratification (°C)

IATD = average indoor air temperature after destratification (°C) (thermostat setting)

Expressing this as the heating energy used before destratification equals (75,147 x 89 x 24 x 60 x 60) / 0.7 = 8255 GJ. This represents an energy saving of 8255 / 20,617 or 40%.

Estimating average indoor air temperature

Most methods for estimating winter energy savings from destratification assume a linear profile for air temperature with height above floor level. In reality the air temperature profile is often not linear. The vertical profile of air temperature inside a space is strongly influenced by the height of heat sources in the building. Most shipping and receiving warehouses in the USA use a number of natural gas fired forced air furnaces mounted about 6 m above floor level.

On-site measurements were made of the air temperatures in a 10 m high shipping and receiving warehouse with two forced air gas furnaces. These measurements indicated that air temperatures were constant to at least 2 m below the roof deck. This suggests that the vertical profile of air temperature was similar to profile D in figure 4. Average indoor air temperature in a space with a D-type vertical profile of air temperature, after thorough mixing, can be estimated by taking the average of two temperature-weighted areas of the indoor vertical profile of temperature above and below the horizontal part of the profile that aligns with the height of the furnaces above the floor. Whenever possible it is advisable to measure the stratified vertical profile of air temperature on site to enable an accurate estimate of average indoor air temperature.

A new method for estimating destratification savings

In a departure from the method suggested by Pignet and Saxena, 2002, the writer suggests a method for estimating the average indoor air temperature when a D type of vertical profile of indoor air temperature exists. This can be done by using Equation 3.

AIT = ((TAH x FA x HAH) + (TT x FA x HBH))/ (FA x (HAH + HBH)) (eq. 3)

= ((31.7 x 5388 x 2.59) + (18.3 x 5388 x 6.4)) / (5388 x (2.59 + 6.4))

= 22.2°C

Where

AIT = Average indoor air temperature (°C).

TAH = Air temperature above heaters before mixing (°C).

FA = Floor area of space (m^2).

HAH = Height above heaters to underside of roof deck (m).

TT = Temperature of air below heaters or setting on heating thermostat (°C) (around head height above floor)

HBH = Height below heaters to floor level (m).

The average seasonal rate of heat loss for a unit temperature difference through the building envelope, UA, in W/K before destratification, can be calculated using Equation 1.

UA = H / LTMTD W/K

= 224,325 / (22.2 – 5)

= 13,042 W/K

The reduced heat load, RHL, due to destratification is calculated using Equation 2.

RHL = (UA) x (IATB – IATD)

= 13,042 x (22.2 - 18.3)

= 50,864 W

Given the efficiency of the gas furnaces is 0.7 the estimated heating energy saved during the sample heating season is:

(50,864 x 89 x 24 x 60 x 60) / 0.7 = 5587 GJ

5587 / 20,617 GJ = 27.1%.

The dollar value of fuel savings over this sample heating season is 5587 GJ at, say, $10/GJ = $55,870.

Figure 1 – a typical regional shipping and receiving warehouse in northern USA

Figure 2 – wall-mounted furnace and large ceiling fan (top right) inside warehouse

Figure 3 – large ceiling fan over warehouse storage racks

Cost of operating large ceiling fans for destratification

Energy-efficient, large, low-speed ceiling fans are the most commonly used for destratification in winter. A shipping and receiving warehouse with a floor area 5388 m^2 would typically have five 6 m diameter fans operating quietly at approximately 20 rpm continuously throughout the heating season. While providing the destratification, the air velocity at head-height above the floor is kept below 0.2 m/s to avoid perception of drafts.

Cost of purchase and installation of the five fans would be approximately US$23,000. At 20 rpm, each fan would use 0.1 kWatts of power. Over the 89 day period of this study these fans would use 5 x 0.1 x 89 x 24 or 1068 kWh of electricity.
At a cost of approximately 6c per kWhr, the operating cost for 89 days is $64.08.

The net annual savings from destratification would be $55,870 - $64 or $55,806. This more than recoups the purchase and installation cost of the fans in a single year. From this example it is easy to see why warehouse owners in cold climates are enthusiastic about destratification.

Validation by a case study

The data used in the two estimates detailed above relate to a 5388 m^2 shipping and receiving warehouse in Middletown NY. The owners of this facility collaborated in a study to evaluate the cost savings of destratification in winter. Natural gas consumption by the heaters along with heating degree-days (base 18.3°C) were recorded for February, March, and April in 2003 before destratification fans were installed.

Similar measurements were made during the same months in 2004 after destratification fans were installed. These data are shown in Table 1. The other facility related data used in this paper were provided by the facility owners.

Given that each winter season is unique, direct comparisons cannot be made. To overcome this, one can compare the GJ of gas required to provide the same indoor temperature of 18.3ºC divided by the severity of the winter season in heating degree days.

In this case:

$100 \times ((6872 / 411) – (4467 / 363)) / 16.7$ or 26.3%

The method by Pignet and Saxena gave a saving of 40%. This saving was 52.1% more than the 26.3% saving actually measured. The method by Pignet and Saxena, modified to better account for the actual vertical profile of indoor air temperature, gave a saving of 27.1%. This was 3.0% more than the 26.3% measured saving. This is within 10% of the measured value, a criteria adopted as acceptable for engineering estimates of this type given the limitations on data and the broad assumptions used.

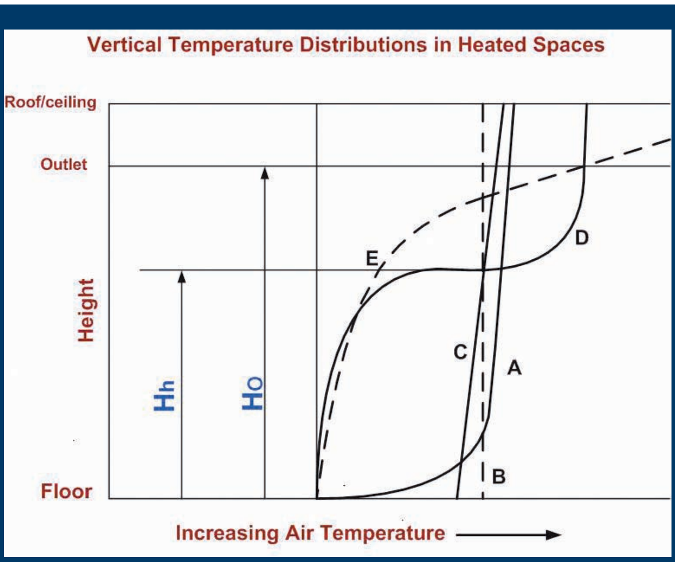

Figure 4 – characteristic vertical profiles of indoor air temperature, determined by location of warm air supply and mixing (Andersen, 1998)

A - heat supplied evenly and close to floor level
B - heat supplied evenly in the space and air is well mixed
C - heat supplied evenly in the room with little air mixing
D - heat supplied from ceiling or upper part of walls with little air mixing.
E - heat from a concentrated source in the upper part of space with little air mixing (after Andersen, 1998).

Where

H = ceiling height
H_h = the height of heater
H_o = the height of ventilation outlet

Month	GJ Gas Used in 2003 Before Destratification	GJ Gas Used in 2004 After Destratification	HDD in 2003 Heating Season	HDD in 2004 Heating Season
Feb.	10,928	6603	562	495
March	6117	4432	409	388
April	3572	2365	262	206
Totals	20,617	13,400	1233	1089
Average	6872	4467	411	363

Table 1 – heating energy used and heating degree days at the facility

Conclusions

Two methods for estimating the winter energy savings from destratification were compared with field data for a three month sample heating season. The first method followed that developed by Pignet and Saxena (2002). This method assumed a linear vertical profile of indoor air temperature. This resulted in an overestimation of the energy savings by 30.9%. The second method was the Pignet and Saxena method modified by the writer to better account for the actual vertical profiles of indoor air temperature. This method overestimated savings by 3.0%, meeting the target of being within 10% of actual measured value.

The benefit of the Pignet and Saxena (2002) method is that it computes a lumped heat transfer coefficient for the building from seasonal heat loss based on heating energy used. This avoids difficulties in measuring, or otherwise determining, the heat transfer coefficient for the building envelope and other losses due to infiltration and ventilation.

The modification suggested by the writer to the Pignet and Saxena method, better takes into account the influence of the type of vertical profile of indoor air temperature on the average indoor air temperature.

Winter conditions vary from year to year. This complicates year to year comparisons of the efficiency of heating energy use. To overcome this difficulty it is suggested that comparisons between years be made on the basis of fuel used per heating degree day for each heating season. ■

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For the past two years Dr Richard (Dick) Aynsley has been director of R & D with Delta T Corp trading as Big Ass Fans in Lexington, Kentucky. Prior to this he was Dean of Engineering Technology and Management at Southern Polytechnic State University, Marietta, USA. He had an academic career from 1969 to 2003. This included appointments as UNESCO Professor of Tropical Architecture and Director or the Australian Institute of Tropical Architecture at James Cook University; Dean of the Faculty of Architecture, Property and Planning, and Head of Department of Architecture at The University of Auckland. His research areas include tropical architecture, natural ventilation, thermal performance of construction, thermal comfort, architectural science and energy efficiency. He is currently chairman of the American Society of Civil Engineers' aerodynamics committee, proposed appointee to ANSI/ASHRAE Standard 55 committee, and chairman of ANSI/AMCA's 230 standard review committee.

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