SINTEF Building and Infrastructure

LECO

MARK MURPHY

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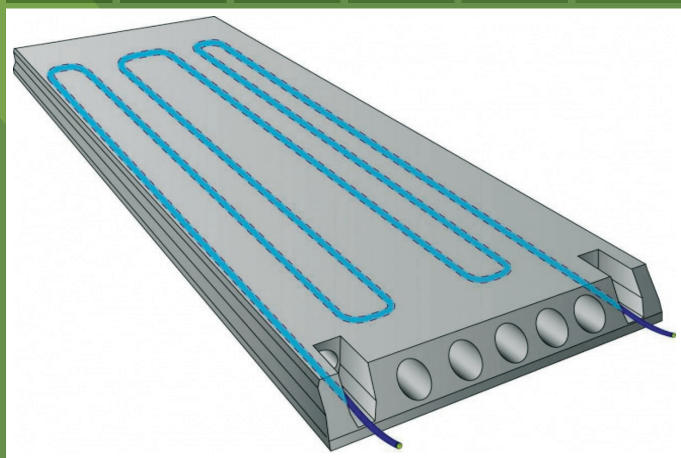
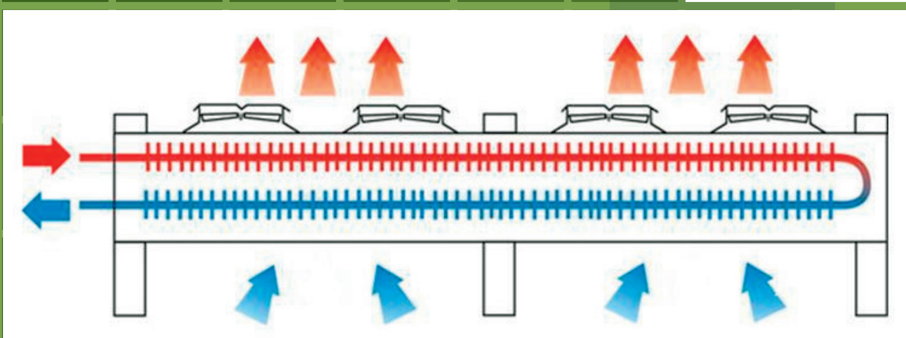
Thermo-active Ceilings & Free Cooling

Using free cooling in combination with thermo-active ceilings for integrated heating and cooling

Project report 52 2010





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Keywords:
Energy, Termo-active elements, low-energy cooling, cooled ceilings, free cooling, thermal mass, building simulation
(Energibruk, kontorbygg)

Project no. 3B015100

ISSN 1504-6958
ISBN 978-82-536-1135-8 (pdf)
ISBN 978-82-536-1136-5 (printed)

Cover, illustration:
Principle sketch of imbedded plastic pipe in concrete.
Source: SpænCom Denmark
Principle sketch of dry fluid cooler. Source: Baltimore Aircoil

40 copies printed by AIT AS e-dit
Content: 100 g munken polar
Cover: 240 g trucard

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Preface

This study is included as a part of the research and development project ”LECO, Low Energy COmmercial buildings”.

Energy use contributed to commercial buildings constituted circa 36 TWh in 2007, which corresponds to approximately 45 % of the energy use in buildings. The potential for conserving energy within this part of the building sector, using current technology, is estimated to 6.5 TWh before 2020. (Lavenergiutvalget, juni 2009)

LECO has the objective to gather in existing and to develop new knowledge pertaining to energy efficient solutions that reduce energy use in commercial buildings. Intensions are to produce guidelines with respectively 50 %, 75 % and 90 % reduction of energy use (Factor 2-4-10) to a typical office building of today. (Reference building =300 kWh/m^2 year.)

In the quest to find energy efficient solutions, this report has been constructed to investigate the savings potential of thermo-active ceilings coupled with free cooling.

The project was completed by Mark Murphy in the autumn of 2009.
Inger Andresen from SINTEF Building and Infrastructure has contributed with quality control of the project report.

LECO er et kompetanseprosjekt med brukermedvirkning (KMB).
Prosjektet ledes av SINTEF Byggforsk og gjennomføres i samarbeid med SINTEF Energiforskning AS, Erichsen & Horgen AS, Entra Eiendom AS, YIT AS, Entro AS, Hunter Douglas AS, Per Knudsen Arkitektkontor AS, Rambøll AS, Skanska AS, og OptoSense AS.
Prosjektet ble igangsatt høsten 2008 og vil pågå til utgangen av 2010.

Vi takker prosjektets partnere og Norges forskningsråd for finansiering av prosjektet.

Abstract

The largest potential for decreasing green house gas emissions, and therewith mitigating the effects of global climate change, comes from improving energy efficiency. Through the integration of heating and cooling systems into building elements, such as the thermo-active ceiling, improvements in energy efficiency can be achieved.

Utilizing thermal mass to buffer temperature variations and to level out peak loads reduces the instantaneous power demands and enables traditional cooling equipment to operate in temperature ranges with higher coefficients of performance. Additional savings in both energy and money can be obtained through the use of free cooling, especially in northern climates. As the coolant temperature in a thermo-active ceiling approaches room temperature, the cooling potential of outdoor ambient air increases. This temperature difference enables free cooling at the mere cost of blowing outdoor air through a heat exchanger.

This paper investigates the savings potential of thermo-active ceilings combined with free cooling using the building simulation software TRNSYS. A reference building is simulated with and without the thermo-active ceiling and free cooling combination through a range of different internal heat gains in a Nordic climate similar to Chicago.

The thermo-active ceiling succeeds in cooling away internal heat gains up to 50 W/m^2. During the majority of the year, the office building has a cooling demand that can be met entirely by free cooling. Less than 10 percent of the annual cooling demand must be obtained in addition to free cooling. The savings potential ranges between 8 and 16 kWh/m^2 when compared to a traditional system using a heat pump to supply cooling.

Table of Contents

1 INTRODUCTION

The largest potential for decreasing green house gas emissions, and therewith mitigating the effects of global climate change, comes from improving energy efficiency. Through the integration of heating and cooling systems into building elements, such as the thermo-active ceiling, improvements in energy efficiency can be achieved. Utilizing thermal mass to buffer temperature variations and to level out peak loads reduces the instantaneous power demands and enables traditional cooling equipment to operate in temperature ranges with higher coefficients of performance. Additional savings in both energy and money can be obtained through the use of free cooling, especially in northern climates.

A thermo-active ceiling utilizes thermal mass activation to supply radiant heating and cooling to a room. This is achieved by embedding pipes into thermally massive materials, such as concrete. The exposed concrete is then allowed to interact with the room. To enhance this interaction, cooled or warmed water is pumped through the embedded pipes in the concrete. By adjusting the water temperature and flow rate, the cooling and/or heating power can be regulated.

With a radiant heater (alt. cooler) covering the entire floor (alt. ceiling), the circulating water temperature approaches room temperature. As the coolant temperature in a thermo-active ceiling approaches room temperature, the cooling potential of outdoor ambient air increases. This enables free cooling at the mere cost of blowing outdoor air through a heat exchanger.

1.1 Objective

- The first objective was to simulate an office building with a thermo-active ceiling that supplies both heating and cooling via pipes embedded within concrete. The circulating water is then pumped outside the building and through a dry fluid cooler (free cooling aggregate), where fans cool the water by blowing outdoor air through the aggregate.
- The second objective was to analyze the savings potential of a free cooling aggregate compared to traditional cooling techniques. To do this, two identical buildings were simulated. One was equipped with thermo-active ceilings and free cooling while the other used heating and cooling to stay within the temperature interval 18-26 degrees.

1.2 Tools

Buildings simulation software TRNSYS 16 with Type 334 Air Handling Unit and Type 511 Dry Fluid Cooler was used to simulate the office building with an active layer in the ceiling and a fluid stream that circulates through the ceiling and the outdoor free cooling aggregate. Thermo-active building elements are integrated into Type 56 Multi-zone Building. The appendix has a description of the simulated components, including how the thermo-active ceiling was setup and how the simulated components are interconnected.

2 BACKGROUND – FREE COOLING

2.1 Free Cooling

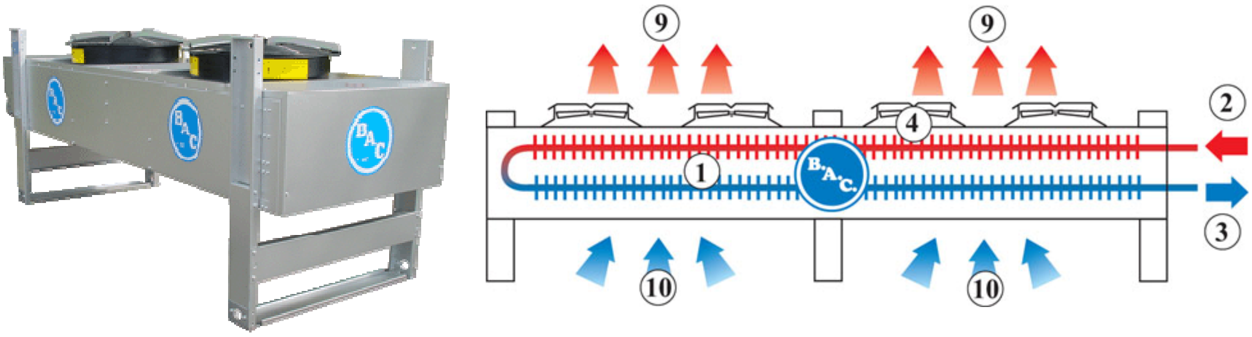


Figure 1: Dry Fluid Cooler (Free Cooling Aggregate)
Source: Baltimore Aircoil [1]

The figures above show what a simple free cooling aggregate can look like and how it works. This simplistic device utilizes the temperature difference between a circulating fluid and the outdoor ambient temperature. If the outdoor temperature is less than the circulating fluid, cooling can be obtained by blowing outdoor air through a heat exchanger (1) with the help of fans (4). The warm water (2) is cooled down to (3) while the incoming outdoor air (10) is warmed up to (9). This process is known as free cooling and the device used is either called a free cooling aggregate or a dry fluid cooler. The latter is the most commonly used term.

2.2 Cooling Potential

The cooling potential of free cooling is dependent upon the temperature of the fluid circulating through the free cooling aggregate and the outdoor ambient temperature. As the coolant temperature approaches room temperature, as in the case of a thermo-active ceiling, the cooling potential of the outdoor ambient air increases.

The system diagram in the figure below shows how the water circulates through the system. The system boundaries are drawn around the free cooling aggregate and a supplementary cooling machine (necessary during the warmest days of the year). Without calculating the temperature of the water flowing out of the thermo-active ceiling, the cooling potential of two different free cooling aggregates was investigated. The cooling system was simulated using Trondheim's weather for one year with a constant water temperature and mass flow entering first the free cooling aggregate and then the supplementary cooling machine.

The free cooling potential, defined as the fraction of the cooling demand covered by free cooling, is presented in the figures on the following page.

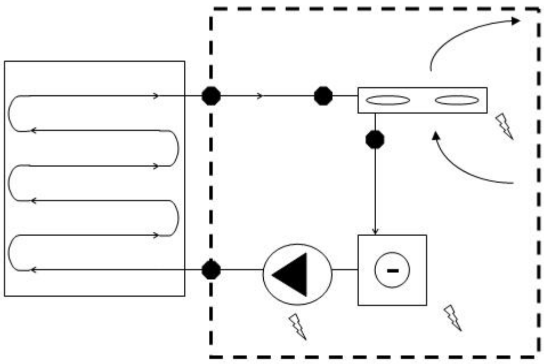
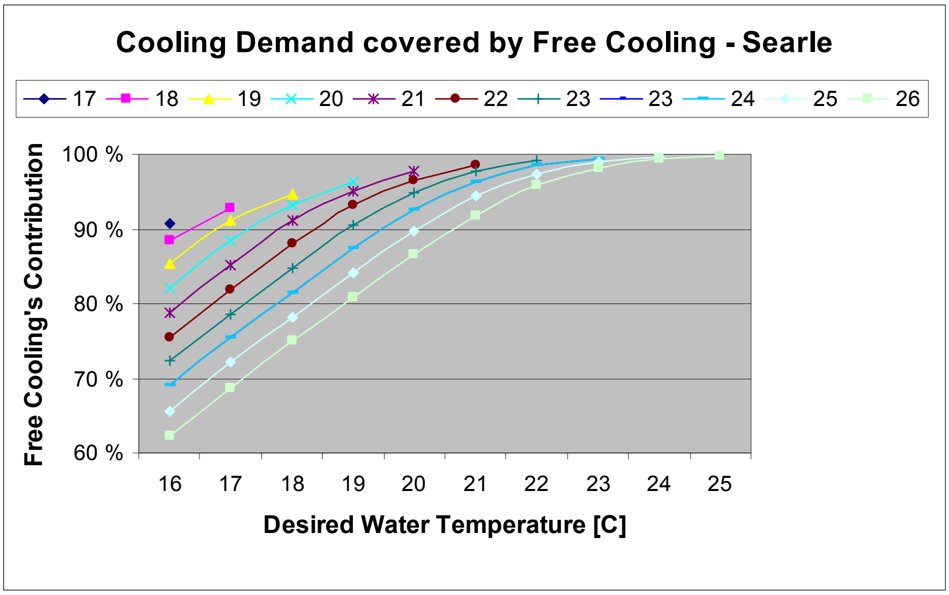
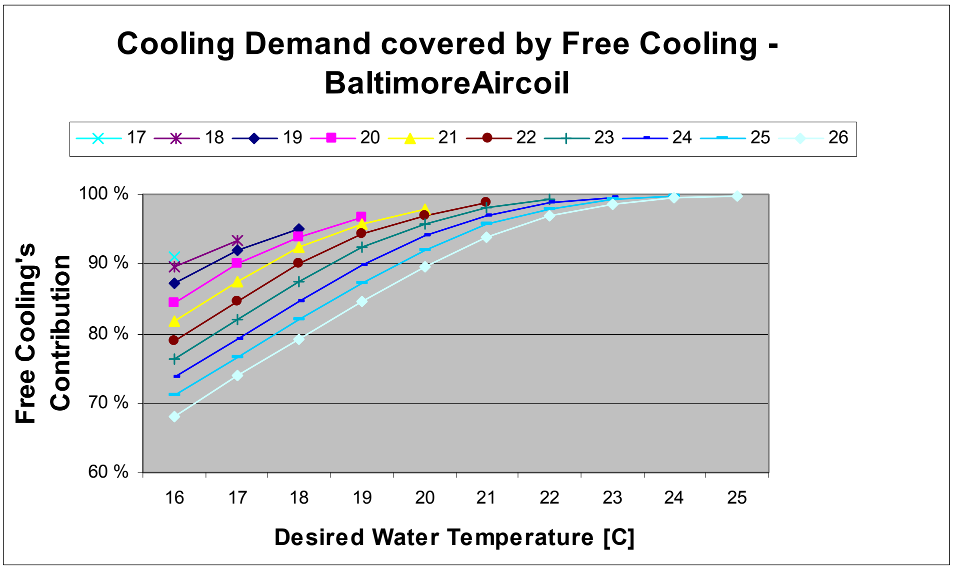


Figure 2: System Diagram with boundaries around the cooling system

[1] http://www.baltimoreaircoil.be/BAC/EU/axicatalog20.nsf/activedocuments/AB0B61D006EDC8D6C12570AB003B99FB?OpenDocument&Language=English





Figures 3 & 4: Cooling Demand covered by Free Cooling in two different free cooling aggregates with inlet temperatures in the legend and desired (cooled) water temperatures on the x-axis

As can be seen in the figures above, the performances of two free cooling aggregates from two different manufacturers are quite similar. The differences between the two are most noticeable when attempting to cool temperatures well above room temperature (20 C) to a few degrees below room temperature.

2.3 Regulation and Control

As the ambient temperature decreases in cooler climates, the cooling capacity of figures 4 and 5 will shift upwards. Slightly warmer climates will cause the curves to shift downwards. This can be compensated for by dimensioning the free cooling aggregate to take a larger flow or by using a partial load. Note however that decreasing the fluid flow too much can result in laminar flow through the free cooling aggregate. In which case, the efficiency of the heat exchanger decreases. When laminar flow occurs will of course depend upon the design of the free cooling aggregate. This and the fact that pumping water is easier than pumping air will advocate using constant water flow and regulating the cooling power with the fan [2].

[2] http://www.novemakulde.no/06/ins/Instr_SDS_sdv.pdf

3 BUILDING SIMULATION

3.1 Development of the used Building Models

Building 1: The building was simulated using Type 56 Multi-zone Building with the following properties

Table 1: Zone Properties of Building 1

Zone Dimensions [m]	Name	A_temp [m^2]
5.7 x 42.5 x 2.4	North	242.5
6.4 x 42.5 x 2.4	Middle	272
5.7 x 42.5 x 2.4	South	242.5

The intermediate floor over the parking garage is simulated with the default GROUND wall using an isothermal boundary of 15 °C on the undersurface. GROUND consists of a thin floor, stone, silence, 24 cm concrete, and 8 cm insulation. The U-value is 0.31 W/m^2K. The exterior walls are based on case study Sluppenveien 17. They consist of plaster, 25 cm insulation, plaster, fictitious air resistance, and stainless steel plating. The U-value is 0.15 W/m^2K. Interior walls are plaster, 5 cm insulation, plaster. The ceiling consists of an active element embedded 6 cm into a 24 cm layer of concrete and followed afterwards by 16 cm insulation. The ceiling is simulated as an intermediate floor using the option: identical boundary conditions.

The fenestration (window to wall ratio) was 40% on the eastern, southern, and western facades. It was 33% on the northern façade. The windows were passive house standard windows with 20% frame and U-value of 0.8 W/m^2K.

The office building has operational hours from 8 am to 8 pm, Monday to Friday. During office hours, the ventilation rate is 5 air circulations per hour. Outside of office hours, the internal heat gain is zero and the ventilation rate is reduced down 1 air circulation per hour. Air leakage is normalized to 0.05 air circulations per hour, which represents a leakage rating of about 0.6 ach^{-1} at 50 Pascal pressure difference.

The building is situated in Trondheim with an orientation of 15 degrees towards the east. Solar shading on the south façade is activated when the total radiation is greater than 140 W/m^2, and it is deactivated when less than 120 W/m^2. The solar shading has an internal and external shading factor of 80%. Artificial lighting switches on when the total horizontal radiation is less than 120 W/m^2, and it switches off when greater than 200 W/m^2.

Building 2: The building above was expanded to include two levels and the zones were remodeled as shown in the figure below:

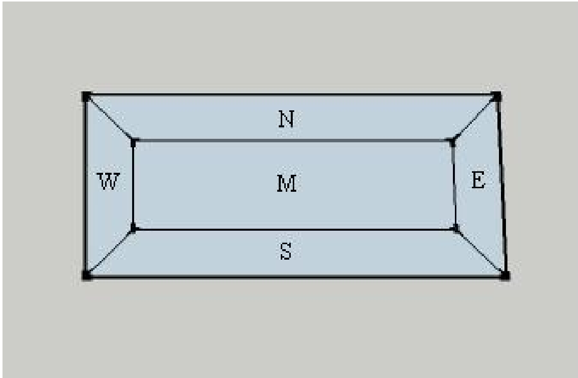


Figure 5: 5 Zone model with 4 meter zone depth

Solar Shading with a shading factor of 80% on the southern façade was extended to include both the eastern and western facades. The buildings orientation was centered towards the south. This model had 10 zones with 10 thermo-active ceilings; 5 of which interacted between two zones.

Simulations reproduced similar results in correspondence with building 1, but the second level had a slightly wider diurnal variation in the operative temperatures. Simulation times were also excessively long.

Building 3: The first building is simulated using the zones of the second building, but the ground floor is simulated as an internal floor with identical boundary conditions. In essence, the second floor of building model 2 is simulated. Active solar shading is used on 3 facades. The middle zone has two active ceilings with a total fluid flow of 640 kg/hr.

Table 2: Zone Areas for Building 2 & Building 3

Name	Zone Area [m^2]
N1	154
E1	55.2
S1	154
W1	55.2
M1	338.1

3.2 Simulation Results

Three cases of different internal heat gains were simulated in order to investigate the performance of thermo-active ceilings on the indoor climate. The internal heat gains started at the normative values given by Table A.2 in NS3031:2007. In total 23 W/m^2, comprising of 8 W/m^2 Lighting, 11 W/m^2 Equipment, and 4 W/m^2 People, was initially simulated. Thereafter the internal heat gains were increased until the indoor temperature varied between 19 and 26 degrees centigrade under the course of a day.

The supply ventilation temperature was constrained to 18 degrees during operational hours, but it was allowed to change for nighttime cooling and morning pre-heating. The possibility of morning pre-heating was activated when the indoor temperature dropped below 19 degrees. Nighttime cooling was activated during non-office hours Monday through Thursday. Both were controlled through an iterative loop on the air handling unit with a setpoint temperature of 20 degrees. Nighttime cooling changed the supply ventilation temperature by adjusting the setpoint temperature after the heat exchanger within the air handling unit, which in turn adjusted the bypass valve. Without increasing the ventilation rate, nighttime cooling is free. Morning pre-heating, on the other hand, requires additional energy input.

Space heating and cooling is controlled through the thermo-active ceiling by regulating the temperature of the water entering the ceiling. The tempering of the circulating water is performed using first a free cooling aggregate and then secondly an auxiliary cooling device. The setpoint temperature of the free cooling aggregate is the desired inlet temperature of the thermo-active ceiling. An iterative loop controls the fan power while an On-Off switch confirms that the ambient temperature is at least one degree colder than the water flowing into the free cooling aggregate.

During the summer when the outdoor ambient temperature becomes too high or the free cooling aggregate does not succeed in cooling the water all the way down to the setpoint temperature, an auxiliary cooling device steps in to ensure that the water entering the thermo-active ceiling holds the desired inlet temperature. During the remainder of the year, the auxiliary cooling device is disabled and the free cooling aggregate covers the entire cooling demand entirely on its own. Minor variations in the inlet temperature are absorbed by the thermal mass in the thermo-active ceiling.

The results of the simulations are found in the table on the following page. The annual coefficient of performance factor is calculated as the total cooling energy divided by the total fan and pumping energy supplied during the course of a year. The extra pumping power required to circulate the water through the system is roughly approximated to 2 kWh/m^2.

Under the given control conditions, it can be seen that the system with thermo-active ceilings and free cooling will have difficulties to clear off an internal heat gain of 60 W/m^2. In order to keep the maximum indoor temperature from exceeding 26 C, the inlet water temperature is 16 to 17 C. This water temperature is pumped continuously in order to load the thermal mass with enough cooling capacity to clear off the following day. The colder surface combined with the 18 degree supply ventilation causes the indoor temperature to drop. In order to ensure 19 C at the beginning of the work day, morning preheating is applied to the ventilation. This results in a substantial increase in the ventilation heating demand, as can be seen in the table when the internal heat gains increase from 40 to 60 W/m^2.

With 60 W/m^2 internal heat gains, the free cooling aggregate covers 75% of the cooling demand. The problem with clearing off such high internal heat gains is within the thermo-active ceiling. A limit of 50 W/m^2 internal heat gains is therefore recommended.

Table 3: Building Simulation Input Data & Performance

	Internal Heat Gains [W/m^2]		
Specific Energy Use [kWh/m^2]	**60**	**40**	**23**
• Ventilation Heating Demand	11.0	6.9	13.8
• Ventilation Cooling Demand	1.7	1.4	0
• Free Cooling Fan Energy	0.8	0.1	0
• Additional Water Cooling Demand	18.6	0	0
• Extra Pumping Energy	2	2	2
Water Inlet Temperature Summer [C]	16	22	cyclic*
Water Inlet Temperature Winter [C]	17	22	cyclic*
Summer Start [hour] (cooling period)	2701	4201	N.A.
Summer End [hour] (cooling period)	7399	5499	N.A.
Simulated Indoor Temperature Variation – Winter [C]	19-26	19-25	19-23
Simulated Indoor Temperature Variation – Summer [C]	19-26	20-26	20-24
Annual Free Cooling COP	19.7	5.0	N.A.
Cooling Demand covered by Free Cooling	74.9 %	100.0 %	N.A.

** The water circulating through the ceiling absorbs heat during the day and releases it at night. The temperature of the circulating water varies between 20 and 24 degrees. The setpoint temperature of the free cooling aggregate was set to 24 C. This temperature was never exceeded, so the water circulated back through the thermo-active ceiling without cooling.*

The outlet temperature will depend upon a multitude of factors, such as the size of the building, the thickness of the active element, the flow rate, the layout of the tubes, the internal heat gains, solar shading, and the controls of the cooling equipment. In the case of 23 W/m^2 internal heat gains, the water temperature leaving the thermo-active ceiling oscillated between 18 and 22 degrees without any cooling. With cooling and higher internal heat gains, the water temperatures leaving the thermo-active ceilings remained within the range of 19 to 24 degrees.

4 SAVINGS POTENTIAL

Two identical buildings were simulated using TRNSYS with an internal heating gain of 50 W/m^2. One was equipped with thermo-active ceilings and free cooling while the other used heating and cooling to stay within the temperature interval 18-26 degrees. The annual energy use is broken into several posts and shown in table 4 below.

Table 4: Annual Energy Use [kWh/m^2]

Annual Energy Use [kWh/m^2]	Normal	Thermo-active + Free
Ventilation Heating Demand	8.0	8.6
Ventilation Cooling Demand	1.7	1.7
Space Heating Demand	0.8	-
Space Cooling Demand	61.0	-
Free Cooling Fan Energy Demand	-	0.7
Auxiliary Water Cooling Demand	-	4.6
Extra Pumping Energy	-	2.0

The light blue represents a thermal cooling demand and the light green represents an electrical demand.

The 0.7 kWh/m^2 free cooling fan energy supplied 59 kWh/m^2 cooling to the circulating water. When combined with the auxiliary water cooling demand, the building would require more cooling than the traditional building. But thanks to free cooling with outdoor air, the fan power needed to supply this amount of cooling is only a tiny fraction.

The savings potential of free cooling is made visible by converting the highlighted thermal cooling demands in table 4 into electrical demands. Using a heat pump, with various coefficients of performance, to convert the thermal cooling demands results in the following table:

Table 5: Savings potential for Thermo-active Ceilings with Free Cooling

System	**Component**	**Thermal Demand**		COP 3	COP 4	COP 5
Normal	Space Cooling Demand	61.0	⇒	20.3	15.3	12.2
Thermo-active ceiling with Free Cooling	Auxiliary Water Cooling Demand	4.6	⇒	1.5	1.2	0.9
	Free Cooling Electrical Demands			2.7	2.7	2.7
			Savings Potential [kWh/m^2]	**16.1**	**11.4**	**8.6**

The difference between the electrical demands of the two cooling systems is the savings potential for thermo-active ceilings with free cooling, which ranges between 8.6 and 16.1 kWh/m^2.

5 DISCUSSION & CONCLUSIONS

When considering the daily temperature variations, the thermo-active ceiling succeeds in cooling away internal heat gains up to 50 W/m^2. Larger internal heat gains may result in unacceptable temperature variations, as shown in table 1.

During the majority of the year, the office building has a cooling demand that can be met entirely by free cooling. Less than 10 percent of the annual cooling demand must be obtained in addition to free cooling, when the internals heat gains are 50 W/m^2 and the building is located in Trondheim.

The results of the building simulations show that the inlet temperatures are around room temperature. The typical temperature range of 12-14 degrees in chilled ceiling panels is unnecessary. Therefore, cooling equipment can be smaller, less complicated, and operate with less power as it is easier to cool temperatures closer to room temperature.

Investment costs for the thermo-active ceiling and free cooling combination may potentially be balanced out by the reduction in heating and ventilation equipment. Radiators and cooling panels are no longer needed and additional floor space usually utilized by these installations is made available.

Based on the simulations with constant inflow temperature during a year, the cooling capacity of free cooling is moderately high so long as the desired cooling temperature does not fall below 16 degrees. Similar results are obtained from two different aggregates with completely different fan powers and design temperatures.

Many models are designed and tested for glycol-water mixes to avoid problems with freezing. A separate external loop with a heat exchanger inside the building envelope would be a recommended solution. A smaller water flow may be easier to cool down, but the risk for laminar flow and reduced efficiency advocates constant water flow near design flow with variable control of the fan power.

The savings potential, shown in table 3, shows that the operational costs will be lower with a thermo-active ceiling. Coupled together with the possibility of marginal investment cost, such a system could easily be economically justifiable.

APPENDIX

A.1 TRNSYS SIMULATION COMPONENTS

Thermo-active Building Elements – Integrated into Type 56 Multi-zone Building
The ceiling is a thermo-active building element with embedded pipes that supply heat or remove heat from the structure. The pipes run parallel to each other with a center to center spacing of 20 centimeter. The pipes have an outside diameter of 20 mm and a wall thickness of 2 mm. The pipes are embedded 6 cm into a 24 cm thick concrete layer. The water circulating through the pipes has a constant mass flow rate of 320 kilogram per hour.

Type 334 Air Handling Unit
The air handling unit is set to 80% temperature efficiency with bypass and frost protection. A bypass on the return air controls how much exhaust air is needed to heat up the incoming fresh air to a set temperature without overheating. A bypass on the incoming fresh, controlled by the temperature of the outgoing exhaust air, prevents frost on the heat exchanger. After the heat exchanger, the supply air can then be heated or cooled before leaving the air handling unit and entering the building.

Type 511 Dry Fluid Cooler
A dry fluid cooler is a free cooling aggregate that uses a fan to blow outdoor ambient air over or through a mesh of heating coils. This provides cooling with a COP much greater than a traditional cooling machine. This component calculates the overall heat transfer efficiency of the free cooling aggregate through varying temperature and flow conditions when given the design parameters of a known dry fluid cooler. The fan power needed to supply the air flow necessary to cool the fluid is calculated using ASHRAE partial load power coefficients and the rated fan power.

Water Loop
The inlet temperature of the circulating water is initially at the setpoint temperature. The water then flows through the thermo-active ceiling and interacts thermally with the concrete ceiling. After leaving the thermo-active ceiling, the water flows from the different zones are mixed together. Then the mass flow rate is scaled up to represent the mass flow coming from multiple levels in order to obtain a mass flow near the dimensioning size of a known free cooling aggregate. This larger flow, with the same temperature as the mixture from the different zones, is pumped through a dry fluid cooler (free cooling aggregate). The free cooling aggregate cools the water until the temperature difference between the water flow and outdoor air is less than one degree. After the dry fluid cooler, the water flow is either cooled additionally with an external cooling source (summertime) or re-circulated back into the building without additional cooling (wintertime).

A.2 TRNSYS SYSTEM DIAGRAMS

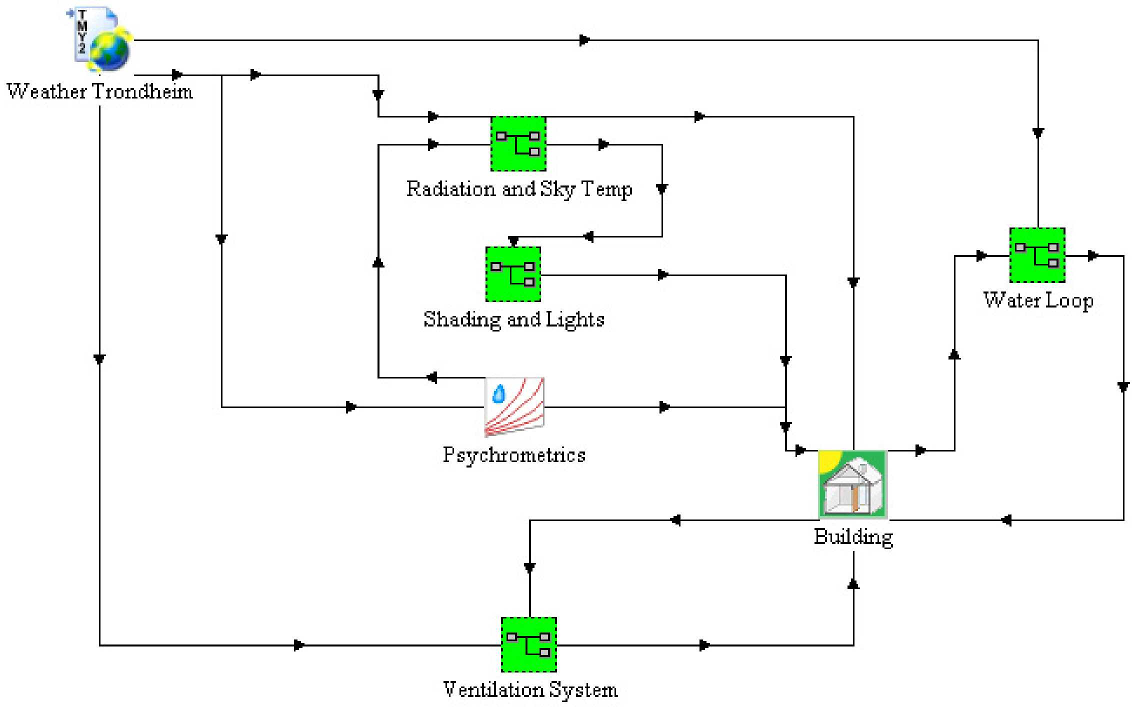


Figure A1: System overview with macros hiding additional components

The radiation and shading macros contain switches and equation editors. The water loop macro and ventilation system macro are expanded and shown in the following figures.

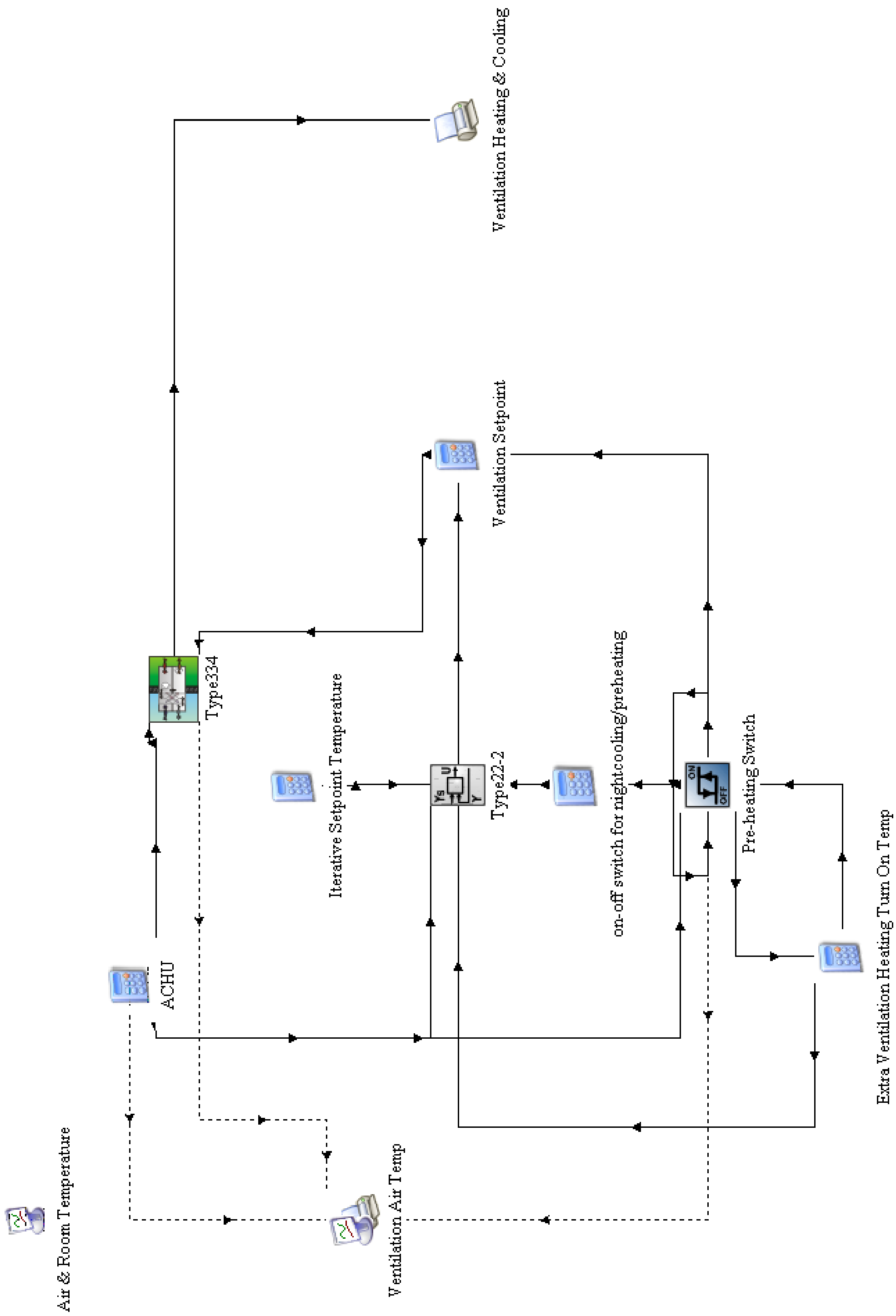


Figure A2: Ventilation System Macro

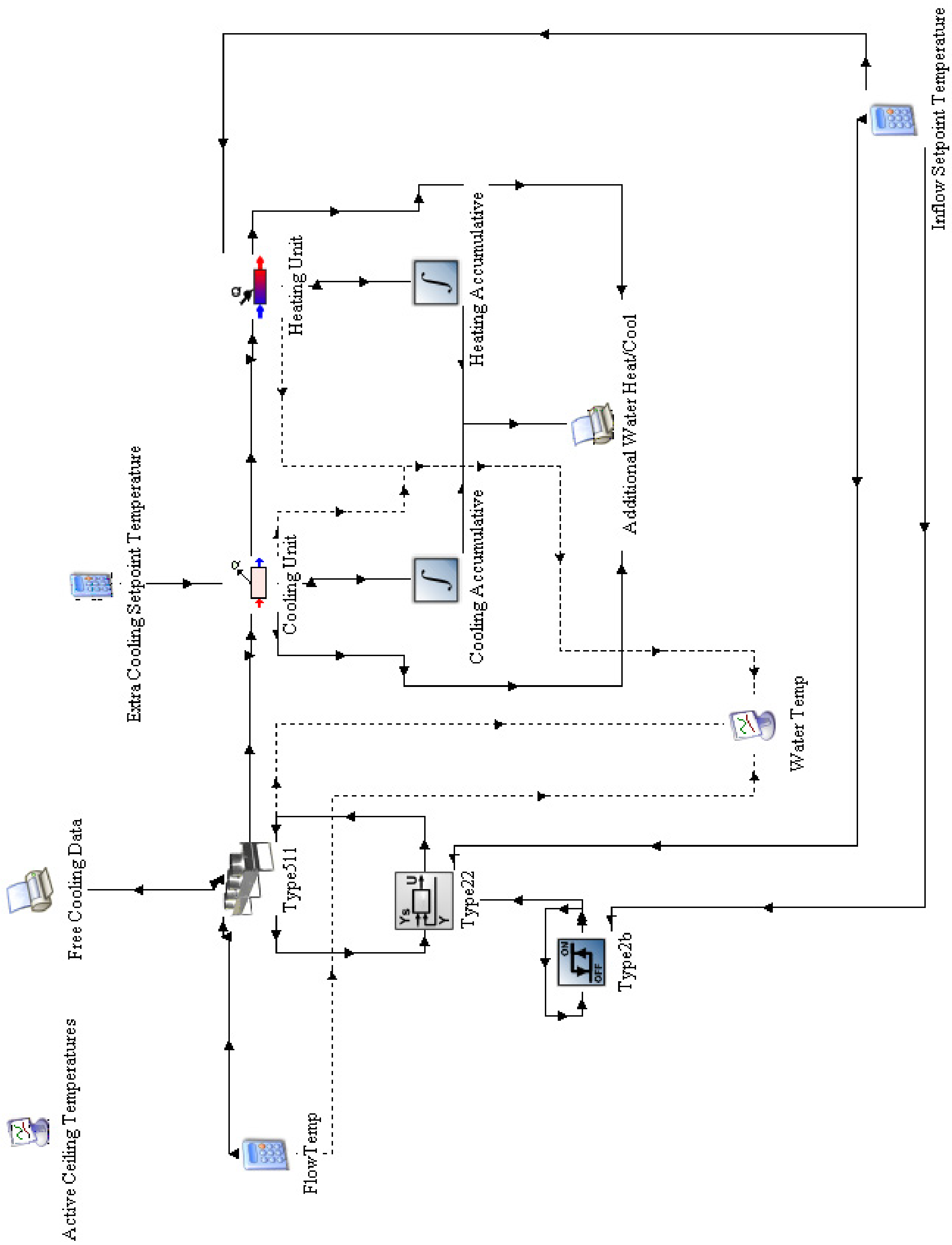


Figure A3: Water Loop Macro

LECO is a knowledge-building project with user involvement.
The project is led by SINTEF Building and Infrastructure and is implemented in corporation with SINTEF Energy, Erichsen & Horgen AS, Entra Eiendom AS, YIT AS, Entro AS, Hunter Douglas AS, Per Knudsen Arkitektkontor AS, Rambøll AS, Skanska AS, and OptoSense AS.
The project started autumn 2008 and will continue until the end of 2010.
We give thanks to the project's partners and The Research Council of Norway for supporting the project.

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