Numerical analysis of thermal comfort in Near-Zero Energy Buildings (NZEB) with light radiant ceilings and diffuse ventilation.

Marie Rugholm Krusaa[*1,2], Christian Anker Hviid[1,2], Jakub Kolarik[1]

1 Technical University of Denmark, DTU
Anker Engelundsvej 1
2800 Kgs. Lyngby, Denmark
**Corresponding author: marrug@byg.dtu.dk*

2 Saint-Gobain Nordic and Baltic A/S
Robert Jacobsens vej 62 A
2300 København S, Denmark

ABSTRACT

Renewable energy sources for heating and cooling buildings usually have temperatures close to room temperature and therefore a limited convertibility potential, i.e. they are of low value. To exploit low-valued energy sources Low Temperature Heating and High Temperature Cooling (LTH-HTC) systems must be developed.

Hydronic radiant ceiling systems with large surfaces for heat transfer are well suited for LTH-HTC. In this paper, a suspended capillary tube ceiling placed on top of perforated gypsum ceiling panels was examined. These panels make it possible to combine a heating/cooling ceiling with diffuse ventilation, also known as leak ventilation, using larger surfaces to provide air into the room instead of diffusers.

Annual energy use in an office building was investigated in the dynamic building simulation tool IDA Indoor Climate and Energy (IDA ICE). The office building contained both offices and meeting rooms. Worst-case scenarios were investigated in the office building, considering heat gains, solar gains and the temperature offset between supply water temperature and room air temperature.

The studies were carried out to determine whether reducing the temperature offset in near-zero energy buildings (NZEB) to ±2-4 °C would be possible without reducing the thermal comfort of building occupants, and whether this would yield energy savings.

The results show that in an NZEB building it would be possible to provide adequate thermal comfort with a minimum use of energy: an energy saving of 36-41 % compared to a fan coil system running with the same temperatures was found to be possible.

KEYWORDS

Diffuse ventilation, energy saving, radiant ceilings, heating, cooling.

1 INTRODUCTION

Buildings are the largest energy-consuming sector and account for 40 % of the total energy consumption and 36 % of the CO_2 emission in the EU (Commission 2017). This growing awareness of energy use has led to a requirement from the European Union that all new buildings must be 'nearly zero energy buildings' (NZEB) by 2020 (European Union 2010). At the same time, there is an increasing focus on indoor comfort and occupants' productivity, which leads to increased demands on heating, cooling and ventilation systems.

The energy used in buildings today is mostly produced from fossil fuels, but as the energy system transforms towards renewable sources, low-valued energy source are being explored

(Hepbasli 2012). Low-valued energy for heating and cooling of buildings are sources with temperatures close to room temperature, so the term Low Temperature for Heating and High Temperature for Cooling (LTH-HTC) was introduced (Babiak and Olesen 2013).
Among these the hydronic radiant systems show considerable potential (Tario and Schmidt 2011). Hydronic radiant systems can be separated intro three types: pipes embedded in the main structure (Thermally Active Building Systems, TABS), pipes isolated from the main structure (radiant surface systems), and radiant heating cooling panels or pipes suspended from the building structure (Kazanci, Olesen, and Kolarik 2016). With these radiant systems, floors, walls and ceilings can be used as surfaces that provide heating and cooling.
Other attempts to use LTH-HTC have been explored as well. One study showed the possibility of using active chilled beams. An active chilled beam supplies air to the room and the room air recirculates within the chilled beam, which gives the chilled beam a higher capacity (Butler et al. 2004). In one study, the temperature offset (the temperature difference between supply air and room air) was ±3 °C (Afshari et al. 2013; Maccarini et al. 2014). This system was installed in an office building in Jönköping, Sweden. The building had been in operation for a year in which the only complaints had apparently been about the office being too cold during the summer (Kretz 2016).
Another way to supply air to the room is the ventilation concept known as diffuse ventilation. The system is characterized by the air being supplied to the occupied room through a relatively large perforated surface; often a suspended acoustic ceiling made from perforated metal ceiling tiles or perforated gypsum tiles. The supply air creates an overpressure in the ceiling plenum that diffuses the air though the ceiling (Hviid and Svendsen 2013). One of the advantages of using a large surface is the reduction of inlet velocity and consequently a reduction of the risk of draught (Yang 2011).
A diffuse ventilation system can be also combined with suspended radiant ceiling panels. As the heating/cooling source is closer to the room a suspended radiant ceiling has a shorter reaction time than Thermo-active Building Systems (TABS).
The present paper reports an investigation of a combination of radiant panels with diffuse ventilation, consisting of gypsum boards with capillary tube mats placed on top. The capillary tubes were of extruded plastic (PEX) and had a small diameter, between 2-5 mm. The tubes were structured in mats, which were evenly distributed across the ceiling.

The objectives were:

- To investigate whether the combination of a capillary tube system and diffuse ceiling ventilation could provide adequate thermal comfort and yearly energy savings with a small temperature offset of only 2-4 °C
- To investigate how system performance responded to changes in heat gains, circulating water temperature and mass flow, i.e. the sensitivity of the solution

2 METHOD

In order to investigate the CApillary Tube Ceiling (CATC) system, a one-room model was constructed in the dynamic building simulation software, IDA Indoor Climate and Energy (IDA ICE) (Equa 2017).
The approach was to create a base unit room-model in a hypothetical office building that could function both as a meeting room and as an office.
The room model had a net floor area of 21.6 m^2, and a total room height of 3.6 m (Figure 1, left). The office building was assumed to be placed in Copenhagen, Denmark and yearly simulations were conducted with the Danish "Design Reference Year" (DRY) weather file (Wang et al. 2013).

The exterior wall was assumed to have a U-value of 0.09 W/m^{2}K and a thickness of 486 mm. The window was South oriented and had a U-value of 0.8 W/m^{2}K, g-value of 31 % and visible light transmittance of 54 %; with a window area of 4.8 m^2 the window to floor ratio was 22 %.
Depending on whether the room model should function as a meeting room or an office the internal loads were as shown in Table 1. The office hours were from 7-17 each weekday, which was also the schedule used for equipment, occupants, lighting and ventilation. The heating and cooling were always on.

Table 1: Simulation input and internal loads during occupancy 7-17

	Office	**Meeting room**
Occupants	7 m²/pers., 80% occupancy 2.5 persons 1.2 MET, 0.75 ± 0.25 clo	2 m²/pers., 90 % occupancy 10 persons 1.2 MET, 0.75 ± 0.25 clo
Equipment	3x50 W	150 W
Lighting	4 W/m^2	4 W/m^2
Shading	Internal shading	Internal shading
Shading factor	0.65	0.65
Ventilation air flow	47 l/s	127 l/s
Supply air temperature	20 °C	20 °C

2.1 Radiant heating and cooling ceiling

To integrate the diffuse ventilation and the CATC system the room model was divided into two zones; an “Office” and a “Plenum” (Figure 1 to the right).
Two types of internal constructions were used. A floor of the office and a ceiling of the plenum was modelled as a 200 mm concrete slab with screed for levelling and floor coating. A suspended ceiling between the office and plenum was modelled as a layer of highly-conductive perforated gypsum board containing graphite particles (λ=0.45 W/m^{2}K). On top of the gypsum, approx. 40 mm of insulation batts (λ=0.037 W/m^{2}K) were placed.

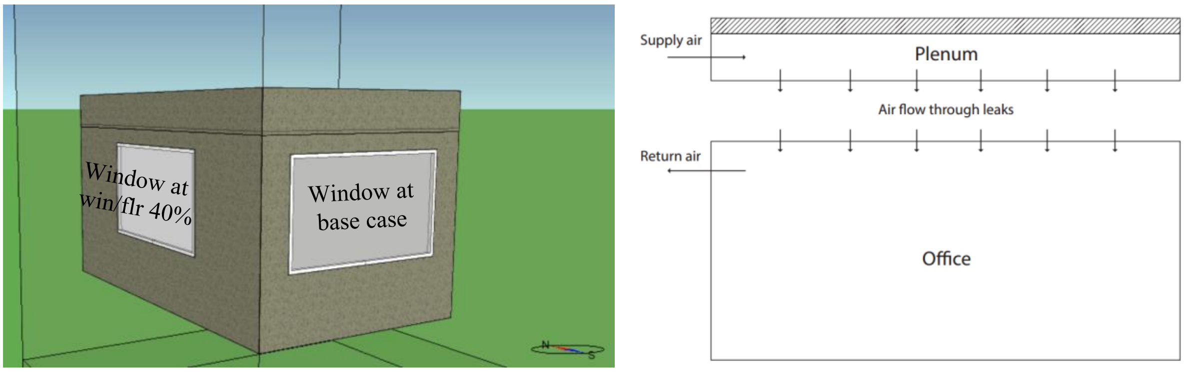

Figure 1: Left: 3D Model from IDA ICE, showing zone model of the office and the plenum with the window and location in the corner of the office building. The window is facing South. Right: Airflow between plenum zone and room zone.

The capillary tubes were modelled using the standard IDA ICE component model for embedded heating/cooling systems (EQUA 2013). The IDA ICE component model represents a plane with controllable temperature placed in the building construction (floor/ceiling slab). The model allows for proportional control of heating/cooling output from the plane based on the operative temperature. The model was then connected to component models of hydronic heating and cooling in IDA ICE (boiler and chiller component models) in which the design mass flow through the radiant ceiling system can be set.

Heat transfer between the embedded system and building construction was represented by a common heat transfer coefficient according to EN 15377-1 (EN 15377 2008) (replaced by standard EN ISO 11855). In the present work, the component model for an embedded heating/cooling system was used to place an idealized heat conducting layer between the gypsum board and the insulation (Figure 2).

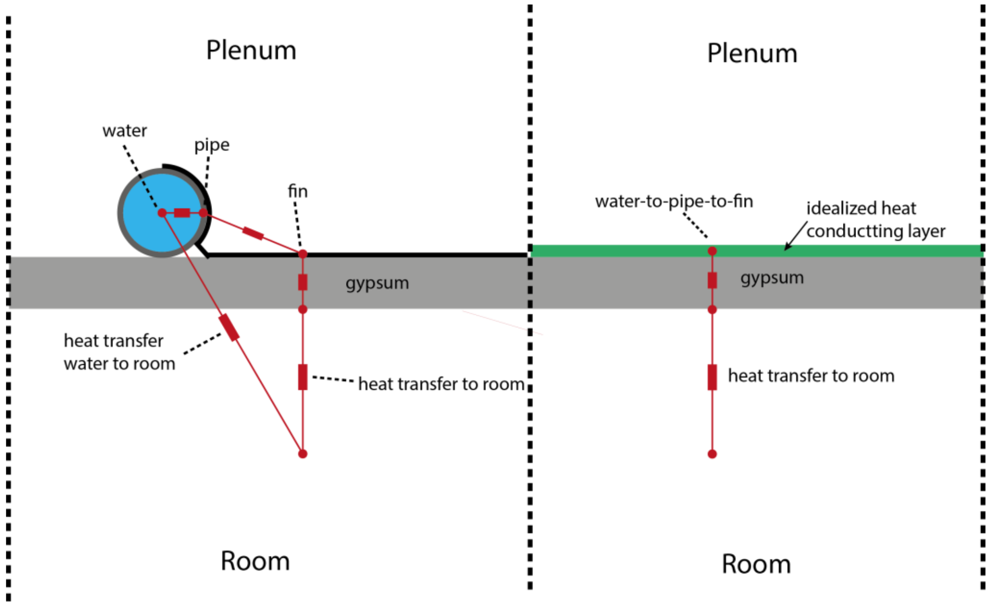

Figure 2: Modelling of heat transfer. Left: EN 15377-1. Right: IDA ICE modelling.

Figure 2 to the left shows how EN 15377-1 calculates heat transfer; to the right are the input parameters in IDA ICE. From a preliminary study of a capillary tube ceiling in combination with diffuse ventilation (Onsberg and Eriksen 2014), the power for heating and cooling was found to be 616 W and 698 W, with a temperature difference at 4.8 K (Design Power in IDA ICE) for a room size 21.6 m² with 60 % of the ceiling covered with mats. To allow for lighting, fire alarms and other installations it the mats covered only 60% of the ceiling. The total heat transfer coefficient from water to room were found by Onsberg & Eriksen to be 7 W/m²K. This was made up of transfer from water-to-pipe-to-fin, heat transfer through the gypsum board and heat transfer to the room, shown in Table 2. The simulation of the mats in IDA ICE was by a constant mass flow, which was the calculated design power, with a temperature offset of only 2 °C. This yielded a mass flow of 0.083 kg/s.

Table 2: Heat transfer coefficients used in the simulation.

	Resistances [m²K/W]	**Heat transfer coefficient [W/m²K]**
Heat transfer to room	0.010	100
Gypsum board	0.022	45
Water-to-Pipe-to-Fin	0.111	9
Sum	0.143	7

2.2 Ventilation

The plenum distributed ventilation air from an air handling unit (AHU) to the office below through intentional cracks and leakages. From the office, the air was extracted and returned to the AHU. For the simulations in IDA ICE, the standard AHU was used with a heating coil and a heat exchanger. The heat exchanger had an effectiveness of 85 % and recovered both

heating and cooling. The specific fan power for the AHU was 800 W/(m^3/s). The ventilation rate used in the investigation was Class I from EN 15251 (2007) for the indoor air quality, which states there should be 10 l/s per person, and 1 l/s per m^2. The total ventilation rate can be found in Table 1.
The air passage between the plenum and office was modelled in IDA ICE by utilizing the leak component feature. The leak component is built up as a pressure flow with the Equivalent Leakage Area (ELA) of 21.6 m. The ELA was defined by the volumetric air flow rate, the discharge coefficient (Cd), which was 1, and the pressure difference, which was set to 4 Pa (Edwards 2006).

2.3 Reference

A reference was created for comparison. The reference system was a CAV ventilation system with fan coils as air terminal devices. The fan coils recirculated the air in the room in order to provide a sufficient heating/cooling capacity. For easier comparison, the only change introduced in the reference was the removal of the radiant ceiling and the introduction of a fan coil as the conditioning source in the room.
The fan coil recirculated with 5.0 l/s per m², and had an estimated pressure drop of 250 Pa with a fan efficiency of 60 %. The system was supplied with the same water temperatures for heating and cooling as the capillary system (22 °C), instead of the water temperatures that would normally (12-16 °C) have been supplied to a fan coil.

3 SIMULATION SCENARIOS

Several investigations were carried out, as both the reference system and the capillary tube system were investigated with different supply water temperatures, different window-to-floor area and g-values. In Table 3, the scenarios are listed and commented upon.

Table 3: Simulated scenarios

Scenario	System	Parameters	Values	Comments
Base case	Capillary	Mass flow ṁ [kg/s] Water temperature T_w [°C] Window-to-floor area [%] g-value of window [%]	0.083 22 22 31	
	Fan coil	Mass flow ṁ [kg/s] Water temperature T_w [°C] Window-to-floor area [%] g-value of window [%]	n/a 22 22 31	
Mass flow	Capillary	Mass flow ṁ [kg/s] of the circulating water	0.035 0.020	The mass flow of the circulating water determines the effective mean temperature of the circulating water and therefore also the heating/cooling capacity.
Tw	Capillary Fan coil	The supply temperature of the circulating water T_w [°C] in the radiant ceiling	20 24	The heating/cooling capacity of the radiant ceiling and the overall yearly thermal comfort level is dependent on the temperature of the circulating water.
Win/flr	Capillary Fan coil	Window-to-floor area [%]	30 40	The ratio of transparent glazing to thermal mass in the room may cause the solar gains to be non-absorbable, in effect raising the temperature of the room.
g-value	Capillary Fan coil	g-value of window [%]	25 38	Some of the solar heat gain from the window could be non-absorbable, depending on the window-to-floor area ratio.

4 RESULTS

Simulations were performed for both office and meeting room in both corner (two façades) and centre configuration (one façade). However, the most critical configurations were found to be corner office and centred meeting room. This section therefore reports only these results. The reported results are energy use, which includes lighting, room heating (district), cooling, and fans & pumps along with the thermal indoor comfort. Thermal comfort was evaluated as hours above 26 °C, according to EN15251 (2007); with 2610 occupancy hours, the 5 % limit means 130 hours.
The daylight factor in the rooms was checked in accordance with the Danish building regulations standard of a minimum daylight factor of 2 % ("The Danish Building Regulations - 6.5.2 Dagslys" 2017), which was achieved in all simulations. This means that the reported window-to-floor area ratios and/or g-value combinations (and corresponding visible light transmittances) do not compromise the level of incoming daylight.

In all simulations, the fan coil system used more energy than the capillary system. Figure 3 shows that the fan coil system used approximately three times more energy on the fans and pumps. Figure 4 show that the fan coil used double the amount for fans and pumps. The fan coil had to be kept running in order to maintain a comfortable temperature in the room.
In general, the accumulated hours above 26 °C were higher with the fan coil system. For both systems, the accumulated hours were highest with a water temperature of 24 °C and all exceeded the maximum permitted (130 hours).

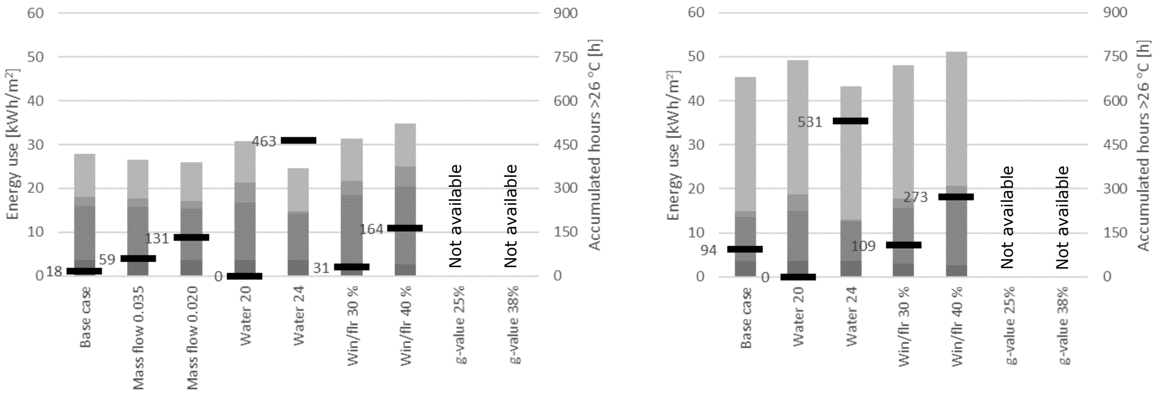

Figure 3: Corner office energy use and overheating. Left: Radiant ceiling system. Right: Fan coil system. Bars of energy use from dark to light grey: Lighting, District heating, Cooling and Fans & Pumps. Solid lines are accumulated hours of operative temperature >26 °C during occupancy

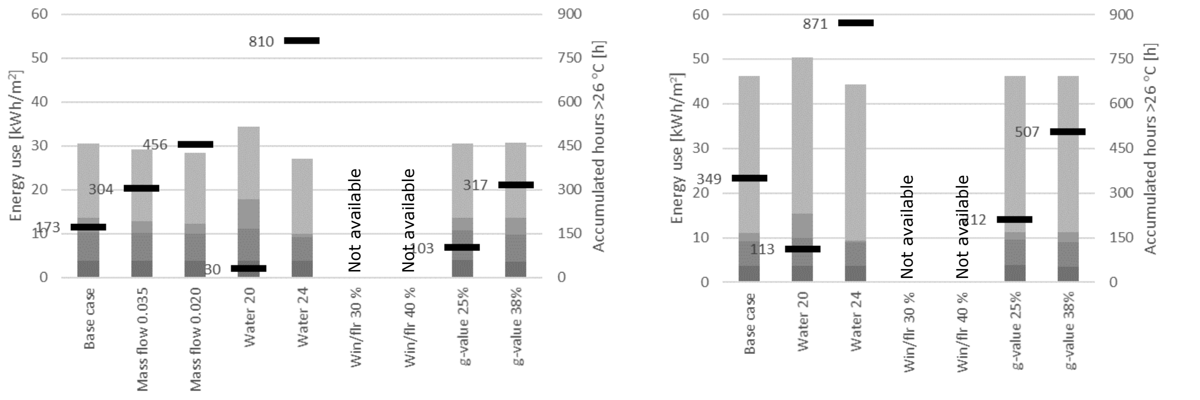

Figure 4: Centred meeting room, energy use and overheating. Left: Radiant ceiling system. Right: Fan coil system. Bars of energy use from dark to light grey: Lighting, District heating, Cooling and Fans & Pumps. Solid lines are accumulated hours of operative temperature >26 °C during occupancy.

For the corner office the base case, with a mass flow of 0.035 kg/s, a water temperature of 20 °C and a win/flr area ratio of 30 %, was well within the requirement of a maximum 130 hours with temperatures above 26 °C. For the centred meeting room the simulations that fulfil the requirement of a maximum of 130 hours were with a water temperature of 20 °C and the lower g-value.

The energy use for the capillary system varied only slightly between cases. Changing the water temperature to 20 °C caused energy use to increase by 10 %, although it did make it possible to achieve comfort in the meeting room. Changing the g-value did not affect the energy use, but did affect the number of overheating hours.

5 DISCUSSION

A conventional fan coil system would operate with a temperature offset of 10 °C. In this investigation, the temperature offset was only 2-4 °C. As a result, the fan coil system was less effective than would be expected. If the supply water temperature had been lowered to 12-16 °C, the fan coil system would probably out-perform the radiant ceiling in terms of thermal comfort, at the expense of much higher energy use for cooling and probably increased risks of draught, and it would not be able to utilize most renewable energy sources.

Diffuse ventilation is difficult to simulate in dynamic simulation programs such as IDA ICE. Two approaches were possible; one was the leak model, which ensured that the airflow was only one way, while the other wouold have been to assume large vertical openings in which the airflow would have been in both directions and not controllable. The limitation of the leakage model is that it is not possible to include the transfer of heating and cooling as the air passes through the surface, or to control the residence time of the air in the plenum before it is supplied to the office.

The resistances were chosen on the basis of the preliminary experimental studies with capillary tube ceiling systems and diffuse ventilation. However, the heat transfer coefficient had only been reported as a value from water to the room. An in-depth study of the individual resistances, convective, conductive and radiative, that make up the total heat transfer of a radiant ceiling in combination with diffuse ventilation, should be conducted to validate heat transfer coefficients assumed in this paper.

6 CONCLUSIONS

Simulations were performed for a radiant ceiling system in combination with diffuse ventilation and a reference case with conventional fan coil units, in which only a few parameters were changed, ignoring the fact that a fan coil system normally operates with higher temperature differences. It was shown that the radiant system had a higher capacity for heating and cooling. The radiant systems were found to have great potential when combined with diffuse ventilation.

- The simulations showed that it was possible to create a system that can provide adequate thermal comfort with minimal energy use.
- Significant energy savings were realized in the capillary system compared with the fan coil system, between 36-41 %.
- Temperature offset of 2 °C for office spaces and 4 °C for meeting rooms is enough to keep the overheating at an acceptable level below 130 hours, with only small differences in energy use.
- Sensitivity was evaluated in terms of thermal comfort: the meeting room was very sensitive to parameter changes and fulfilled the overheating requirements only with the lowest simulated water temperature and the lowest g-value. The office was more robust and tolerated higher heat gains and lower mass flows.

7 ACKNOWLEDGEMENTS

Financial help was provided by Innovation Fund Denmark and Saint-Gobain Nordic A/S.

8 REFERENCES

Afshari, Alireza, Rouzbeh G Norouzi, Göran Hultmark, and C Niels. 2013. "Two-Pipe Chilled Beam System for Both Cooling and Heating of Office Buildings." *11th REHVA World Congress and 8th International Conference on Indoor Air Quality, Ventilation and Energy Conservation in Buildings*, 16–19 June, 2013, Prague, Czech Republic.

Babiak, Jan, and Bjarne W Olesen. 2013. *Low Temperature Heating and High Temperature Cooling Federation of European Heating and Air Conditioning Associations*.

Butler, David, Jonas Gräslund, Jaap Hogeling, Erik L. Kristiansen, Mika Reinikainen, and Gunnar Svensson. 2004. *Rehva 05: Chilled Beam Application Guidebook*. Edited by Maija Virta. *Design*. 2. edition. Vol. 5. REHVA.

Commission, European. 2017. "Buildings - European Commission." *European Union*. https://ec.europa.eu/energy/en/topics/energy-efficiency/buildings.

Edwards, Rodger. 2006. *Handbook of Domestic Ventilation*. https://books.google.dk/books?id=xGcABAAAQBAJ&hl=da&source=gbs_navlinks_s.

EN 15377. 2008. "Varmesystemer I Bygninger – Projektering Af Indstøbte Vandbaserede Systemer Til Overfladevarme Og Overfladekøling – Del 1 : Fastlæggelse Af Dimensionerende Varme- Og Kølekapacitet Heating Systems in Buildings – Design of Embedded Water Base."

EQUA. 2013. "User Manual IDA Indoor Climate and Energy," no. February.

Equa. 2017. "IDA Indoor Climate and Energy. EQUA Simulation AB." http://www.equa.se/en.

European Union. 2010. "Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the Energy Performance of Buildings." http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32010L0031&from=EN.

Hepbasli, Arif. 2012. "Low Exergy (LowEx) Heating and Cooling Systems for Sustainable Buildings and Societies." *Renewable and Sustainable Energy Reviews* 16 (1). Elsevier

Ltd: 73–104. doi:10.1016/j.rser.2011.07.138.
Hviid, Christian Anker, and Svend Svendsen. 2013. “Experimental Study of Perforated Suspended Ceilings as Diffuse Ventilation Air Inlets.” *Energy and Buildings* 56. Elsevier B.V.: 160–68. doi:10.1016/j.enbuild.2012.09.010.
Kazanci, Ongun B., Bjarne W. Olesen, and Jakub Kolarik. 2016. “Low Temperature Heating and High Temperature Cooling in Buildings.” DTU. http://www.rehva.eu/publications-and-resources/eshop/eshop.html?tt_products%5BbackPID%5D=6&tt_products%5Bproduct%5D=35&cHash=32bd42e0a51e537b90685ebda3d816d4.
Kretz, Mark. 2016. “Huset Med Självreglerande Klimatsystem.” *Energi & Miljö*. http://www.energi-miljo.se/sites/default/files/energimilj_0010_low_sid_16-20.pdf.
Maccarini, Alessandro, Alireza Afshari, Niels Christian Bergsøe, Göran Hultmark, Magnus Jacobsson, and Anders Vorre. 2014. “Innovative Two-Pipe Active Chilled Beam System for Simultaneous Heating and Cooling of Office Buildings.” *Isiaq* 2020.
Onsberg, Rasmus, and Morten Skyum Eriksen. 2014. “Investigations and Development of Capillary Thermal Ceiling Systems with Integrated Ventilation,” 179.
Tario, H., and D. Schmidt. 2011. “Annex 49 - Summary Report.” http://www.annex49.info/download/summary_report.pdf.
“The Danish Building Regulations - 6.5.2 Dagslys.” 2017. Accessed June 16. http://bygningsreglementet.dk/br15_02_id102/0/42.
Wang, P.G., M. Scharling, K.P. Nielsen, K.B. Witchen, and C. Kern-Hansen. 2013. “2001-2010 Danish Design Reference Year.” Copenhagen.
Yang, Honglu. 2011. “Experimental and Numerical Analysis of Diffuse Ceiling Ventilation.” *Master Thesis*, no. August.