THE DESIGN OF A DECENTRALIZED VENTILATION SYSTEM FOR AN OFFICE IN SINGAPORE: KEY FINDINGS FOR FUTURE RESEARCH

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ABSTRACT

In this paper, we present what was learned in the research & design process of a decentralized ventilation system with chilled ceilings for a commercial office in Singapore. We make two key observations from the knowledge gathered. First, we observe, in quantitative terms, that present-day radiant cooling panel products may not provide sufficient sensible cooling capacity for commercial offices in hot and humid climates. However, upon considering the use of passive chilled beams as an alternative chilled ceiling product, we do observe that a decentralized ventilation system comprising both recirculating and dedicated outdoor air fan coil units may reduce daily electricity requirements for air-conditioning in Singaporean office spaces by over 15%.

Keywords: decentralized ventilation, radiant cooling, chilled ceilings, commercial buildings, hot and humid climates

INTRODUCTION

In the pursuit of furthering empirical research on the comparison between centralized and decentralized air-conditioning and mechanical ventilation (ACMV) systems [1], a new research project is underway in Singapore in which a 550 m^2 office will be designed by researchers in collaboration with professional partners and fit-out with a prototype decentralized ACMV system similar to the system previously evaluated by Meggers et al. [2]. The system will couple decentralized ventilation units - configured to provide primarily latent cooling - with a high-temperature chilled ceiling system for sensible cooling. Learning from the design phase of this project has allowed for the establishment of some design principles on the adaptation of decentralized ACMV systems for, at least, persistently hot and humid climates. Some of these principles are to be explored in this paper under the context of the pilot implementation project, such as:

- evaluating the applicability of chilled ceiling technologies for hot and humid climates; and
- simulating the performance of various state-of-the-art decentralized ventilation systems and discussing some of their benefits and drawbacks.

1.1 The case study building area

The project implementation area fits within a larger, four-storey, 20,000 m^2 multi-purpose building under construction in Singapore at time of this writing. A provisional floor plan is shown in figure 1. The entire building, including the project area, has been designed to achieve Singapore's "GreenMark Platinum" accreditation status[1]. The main implication of this for the current analysis is that the indicated façades in figure 1 are targeted to yield a net heat gain coefficient[2] no more than 40 W/m^2 at any time of year. Not indicated in the figure is that the floor-to-ceiling height for the project implementation area is 4.0 m.

In predicting total sensible cooling loads for the project space, three interior zones are isolated and described further in figure 1: a private office located adjacent to a façade, a centrally-located open office area, and a boardroom that can also serve as an auxiliary office. Design conditions for internally- and externally-driven heat gain parameters are provided by the project's local engineering consulting team[3]. The design thermal comfort conditions of the office space is 24 °C and 50% relative humidity when occupied. This results in a targeted indoor dew-point temperature of 14.5 °C.

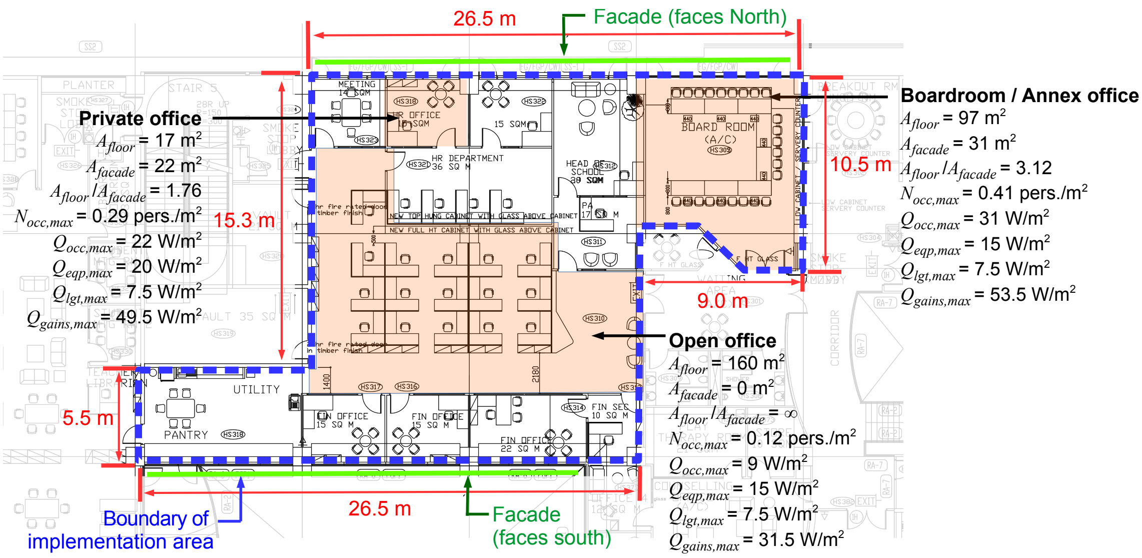

Figure 1: Provisional floor area of implementation area for pilot project in Singapore; a 550 m^2 area on a single floor within a four-storey 20,000 m^2 multipurpose building

2 ON THE APPLICABILITY OF CHILLED CEILING TECHNOLOGIES FOR SENSIBLE COOLING IN SINGAPORE

During the research and design phase of the pilot project, it was planned to identify a radiant cooling panel product that would satisfy the entire sensible cooling energy load of the project implementation area. Doing so would provide an opportunity to achieve significant improvements to chiller plant efficiency in the long-term. As the sensible cooling delivered by chilled ceilings could be achieved using chilled water at relatively high temperatures, it would become feasible to implement, in the future, a low-lift chiller with COP exceeding 9-10 [3].

[1] For more information, see `http://www.bca.gov.sg/greenmark/green_mark_buildings.html`

[2] including convective infiltration gains, solar radiative heat gains, and conduction gains

[3] peak occupant density and electrical appliance layout is predicted directly from the interior floor plan (75 W/person sensible heat gain assumed for human occupants), LED lighting assumed throughout with power density of 7.5 W/m^2

However, an interesting caveat was encountered when assessing the applicability of radiant panels to this project. Figure 2 has been produced to elaborate on this. It was generated upon a study of several commercial products available in the radiant cooling and passive chilled beam market[4]. The vertical axis of the figure provides the maximum permissible floor-to-façade area ratios for a given chilled ceiling technology and heat gain conditions, both internally- and externally-generated. When this figure was compared against the three building zones identified in figure 1, it was found that only the open office area would have been suitable for radiant panels. The private office and board room could only be sensibly cooled with passive chilled beams, comparatively larger devices in terms of equipment height.

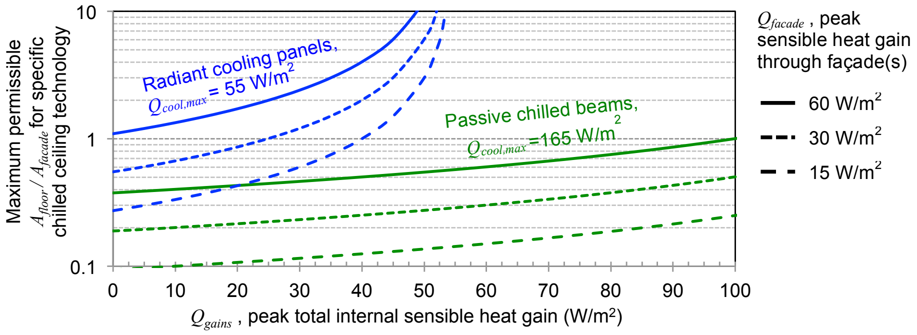

Figure 2: Maximum permissible "floor-to-façade" ratio for total sensible cooling demand to be met by chilled ceiling technology; assumes indoor air conditions of 24.5 °C, 55% relative humidity, and 17.5 °C water supply temperature for chilled ceiling system

What makes this finding interesting is that the design conditions facing the project space are not particularly unique for Singapore. In fact, deliberately optimistic, or low values for interior and exterior heat gains were targeted due to the overall design objectives of the project (i.e., to achieve Singapore GreenMark Platinum status). Thus, to make the project area applicable for radiant panels, it seems it would have been required to broadly reconfigure the interior layout of the project space and more-or-less combine all spaces into a single large open area. Alternatively, it could have been proposed to lower the design supply water temperature of the chilled ceiling panels, thereby increasing their cooling capacity. However, this would have required a reduction to indoor air humidity set-points, in order to avoid surface condensation, resulting in a penalty on energy consumption given Singapore's persistently humid climate. Thus, in lieu of these findings, it was decided to employ passive chilled beams of the type assessed in figure 2.

An expansion of this analysis is warranted, particularly on the general choice between radiant ceiling panels and passive chilled beams. For instance, it's notable that the former are applicable to both heating and cooling applications, whereas the latter are cooling-specific.

3 COUPLING OF CHILLED CEILING SYSTEM WITH DECENTRALIZED VENTILATION UNITS

Whilst the chilled ceiling system is intended to satisfy the majority of sensible cooling energy demand, a mechanical ventilation system is required to satisfy fresh air require-

[4]Products reviewed: ECOPHIT Activation Board (http://www.ecophit.com), REHAU Akustikkuhldecke mit Lochbild 6/18 R (http://www.rehau.com), and TROX PKV (http://www.trox.de)

ments and latent cooling loads. In keeping to the decentralized approach sought by this work, a system configuration was chosen in line with the illustration of the project area's boardroom shown in figure 3. For each interior zone in the project area, displacement ventilation would be provided from a mixture of airflow supplied by two decentralized ventilation units installed in the nearest façade sections. Form factor constraints on the integration of ventilation units in the façade played a significant role in the selection of candidate ventilation unit products - the cross-sectional dimensions of any ventilation unit could not exceed 600 mm x 600 mm.

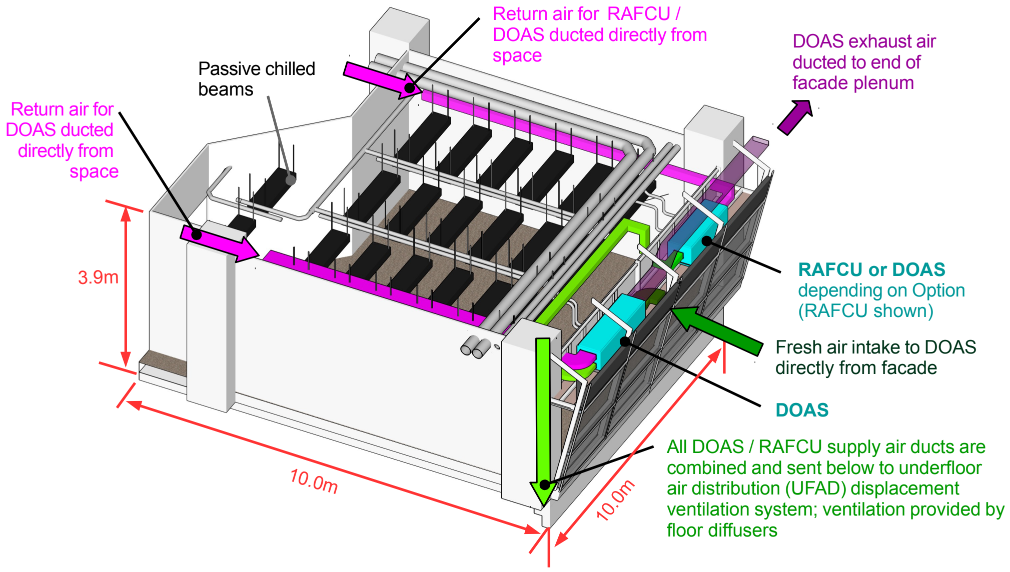

Figure 3: Overview of boardroom zone within project area with chosen decentralized ACMV configuration

Another constraint on the selection of ventilation units was the requirement for passive forms of reheat in order to satisfy minimum supply air temperature requirements for the displacement ventilation system. Active reheat, via heating cools, is prohibited in Singapore, yet supplying untreated off-coil supply air through floor diffusers could lead to thermally uncomfortable conditions for occupants. Hence, two candidate decentralized ventilation units were chosen for analysis: 1) a dedicated outdoor air system (DOAS) with integrated energy recovery wheels; 2) a fan coil unit with integrated heat pipe that could serve in either DOAS or 100% recirculated air (RAFCU) mode. From this, we identified four plausible system configurations: 1) a 100% outdoor system provided by two heat-pipe fan coil units operating in DOAS model, 2) the same approach but using wheel-based DOAS units, 3) a mixed system of heat pipe fan coil units where one unit serves as a DOAS and a second as an RAFCU, and 4) the same approach although replacing the heat pipe-based DOAS with a wheel-based DOAS. These options are respectively identified by systems A to D in figure 4. Steady-state system performance specifications of identified commercial products are also provided.

More information about the theoretical performance of the wheel-based DOAS units can be found in Mumma [4]. Of the configurations shown in figure 4, it should be noted that the gross fan power of the wheel-based DOAS units is much higher the fan coil units, even under the same rated air flow rates. This is attributed to the high pressure drop induced across the unit's recovery wheels as well as the narrow flow channels permitted for supply and return air streams due to the form factor of the unit.

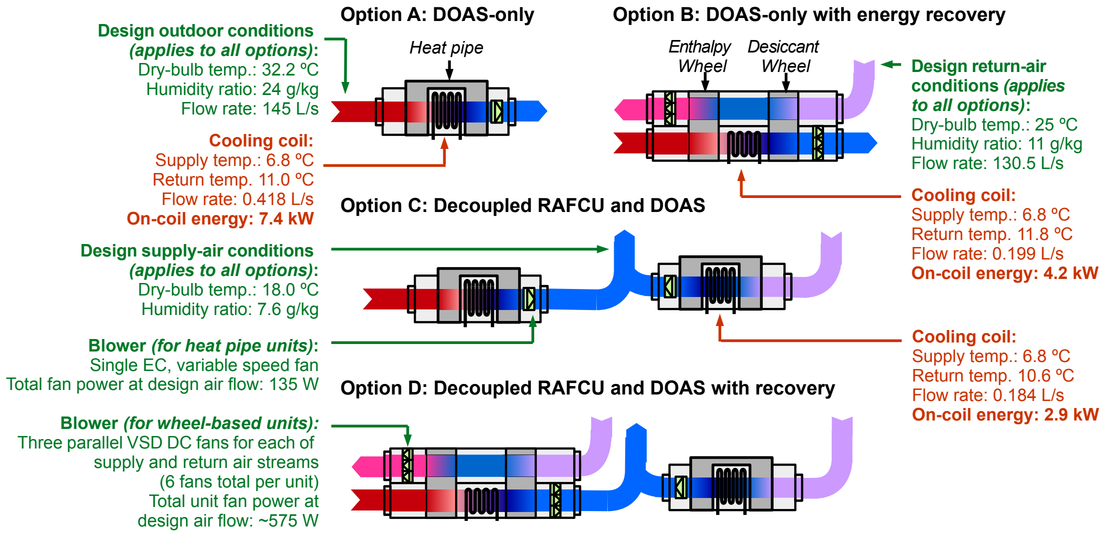

Figure 4: Possible configurations for decentralized ventilation systems coupled with chilled ceilings

Regarding the system's control logic, two approaches have been considered. For Options A and B, it's assumed a 2-stage control logic is employed. During normal operation cycles: 1) the DOAS is operated at whichever minimum flow rates (air and water) achieve both latent cooling and fresh air requirements; 2) the passive chilled beam network operates at whichever minimum chilled water flow rate and temperature required to satisfy sensible cooling requirements and avoid condensation. For Options C and D, a 3-stage priority control logic is employed. During normal operation cycles: 1) the DOAS system is operated at whichever minimum flowrate satisfies fresh air requirements, 2) the RAFCU operates at whichever minimum flowrate satisfies latent cooling loads not met by the DOAS, 3) the passive chilled beam network operates as above to satisfy remaining sensible cooling loads.

In Rysanek et al. [5], a TRNSYS simulation was developed for predictive performance evaluation of the ventilation system's thermodynamic components and control logic. That study evaluated a single control zone, the board room shown in figure 3, and compared the performance of Option D with a conventional centralized air handling system. In figure 5, we present results of an expanded TRNSYS simulation of Options A, B, and C undertaken for this study. It illustrates daily average electrical energy requirements for operation of the entire ACMV system, barring pumps for the low-temperature chiller plant. A constant, central chiller COP of 4 was used for all conversions of on-coil energy to electrical energy.

On review of the net simulation results in figure 5, it was decided to adopt Option D for the implementation project. We view its predicted performance to be attributed to the system ensuring outdoor air is introduced to conditioned spaces only when needed for indoor air quality, and recovers enthalpy from the exhausted air stream when doing so. We also observe that, in comparison to the central air handling system, the decentralized system provides improved controllability of indoor air, humidity, and dry-bulb temperatures, ensuring that neither property is over-satisfied. However, as with our analysis of chilled ceiling technologies, these are preliminary findings that warrant further analysis.

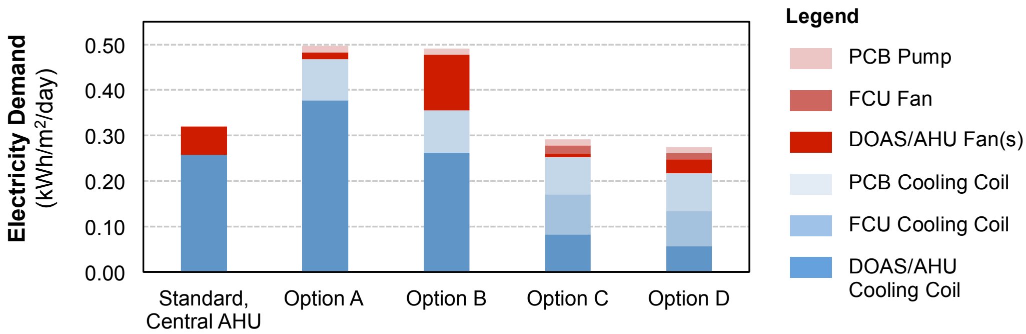

Figure 5: Estimated average daily electricity requirements for assessed decentralized ventilation options

4 CONCLUSIONS

In a brief study, we have examined a few technical aspects of the adaptation of chilled ceilings and decentralized ventilation units for hot and humid climates. The backdrop for this analysis has been the design process undertaken for the fit-out of a real-world office in Singapore with such a system. Many of the preliminary findings in this paper warrant further study, much of which will be conducted empirically in the pilot project area over the coming years. Nevertheless, in the conducted performance simulation, with results shown in figure 5, it was found that a decentralized ventilation system which couples small packaged outdoor-air fan coil units, recirculated-air fan coil units, and a chilled ceiling, could reduce total daily electricity consumption for air-conditioning use by at least 15% in a commercial office space in Singapore.

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