Energy and Buildings 71 (2014) 28–37

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Stuck in a stack—Temperature measurements of the microclimate around split type condensing units in a high rise building in Singapore

Marcel Bruelisauer[a,*], Forrest Meggers[b], Esmail Saber[a,b], Cheng Li[a,c], Hansjürg Leibundgut[d]

[a] Future Cities Laboratory, Singapore-ETH Centre, Department of Architecture, ETH Zurich, Switzerland
[b] School of Design and Environment, National University of Singapore, Singapore
[c] School of Computer Engineering, Nanyang Technological University, Singapore
[d] Chair of Building Systems, Institute of Technology in Architecture, Department of Architecture, ETH Zurich, Switzerland

ARTICLE INFO

Article history:
Received 7 June 2013
Received in revised form 24 October 2013
Accepted 12 November 2013

Keywords:
Air-conditioning
Tropical climate
Energy efficiency
Heat rejection
Split units
High-rise buildings
Temperature rise
Field measurements
Condensing unit

ABSTRACT

The use of air-conditioning, the largest energy demand for buildings in the tropics, is increasing as regional population and affluence grow. The majority of installed systems are split type air-conditioners. While the performance of new equipment is much better, the influence of the microclimate where the condensing units are installed is often overlooked. Several studies have used CFD simulations to analyse the stack effect, a buoyancy-driven airflow induced by heat rejected from condensing units. This leads to higher on-coil temperatures, deteriorating the performance of the air-conditioners. We present the first field measurements from a 24-storey building in Singapore. A network of wireless temperature sensors measured the temperature around the stack of condensing units. We found that the temperatures in the void space increased continuously along the height of the building by 10–13 °C, showing a significant stack effect from the rejected heat from condensing units. We also found that hot air gets stuck behind louvres, built as aesthetic barriers, which increases the temperature another 9 °C. Temperatures of around 50 °C at the inlet of the condensing units for floors 10 and above are the combined result, reducing the unit efficiency by 32% compared to the undisturbed design case. This significant effect is completely neglected in building design and performance evaluation, and only with an integrated design process can truly efficient solutions be realised.

1. Introduction and background

While we researchers strive to increase energy efficiency and reduce greenhouse gas emissions from building operation, society continues to increases its expectation of the built environment. Just as European societies moved away from fireplaces and ovens as central heating technology became available, now developing countries expect more and more air conditioning. This is especially true in the rapidly growing market for individual split type or window type air-conditioning units, which ever more people are gaining access to in the developing world and large population centres in the tropics. If we are to address conglomerate growth of energy demand we must address the large-scale design and installation of these small system. The unchecked installation of split units has had a dramatic effect on façade aesthetic and form in places like Singapore, and the heat rejected by these systems is also largely unaddressed. We present for the first time experimental findings on the impact on local temperatures of the heat rejected from split units installed throughout a 24 story building in Singapore. Our results uncover a major influence on the temperatures adjacent to the building that will affect both comfort and the expected performance of the system, significantly lowering the efficiency of the air-conditioning equipment and degrading the comfort.

This reduced performance erodes away successes in increased efficiency in buildings, which must be broadly addressed because the energy used to create, operate and deconstruct buildings is a major anthropogenic contributor to greenhouse gas emissions and thus climate change. 76% of the total electricity consumption

* Corresponding author. Tel.: +65 85870713.
E-mail address: bruelisauer@arch.ethz.ch (M. Bruelisauer).

http://dx.doi.org/10.1016/j.enbuild.2013.11.056
0378-7788

Fig. 1. Typical installation of split unit condensers in a crowded and hidden location.

in the US is used for buildings [1]. Due to their static nature and much untapped improvement potentials, buildings also represent a major opportunity for the reduction of further emissions. In the hot-humid tropics of Singapore, roughly 50% of the energy consumption in buildings is used for air-conditioning [2]. In 2007, 75% of all households were (partly) air-conditioned, a number that has certainly increased since [3]. Similar developments are expected in surrounding countries with increasing population and wealth.

By proxy there is evidence of the rise in the simple air conditioning solutions in the production of R-22, a refrigerant commonly used in small air-conditioners. It has been shown to be rapidly rising in developing countries [4]. This is a dangerous indicator for the further development of climate change, primarily in regard to the high global warming potential of R-22, but also as a significant indicator for the expanding installation of these types of small units. They are often sold as DIY units with a lack of professional installation that may address issues of proper spacing, setbacks from walls, and adequate air supply, all of which degrade an already limited performance. Even without the proxy data of R-22, it only takes a quick look around any of the rapidly growing cities in the tropics to realise the prevalence of these systems as shown clearly in Fig. 1.

In Singapore, one of the most developed of the cities in the tropics, efforts are being made to try to maximize the performance of such systems. One of the efforts, the Green Mark Scheme, a sustainable building certification scheme, was launched to promote sustainability in the built environment. They aim to have 80% of buildings Green Mark certified by 2030 [5], which will place a minimum efficiency on the installation of split units. Still the standard itself speaks to the inefficiency of these systems as buildings that use split units are rewarded with system efficiencies 33% lower than buildings with central chillers [6]. Green Mark certification only applies to whole building projects, but even at the consumer level Singapore has implemented a tick system to signify the quality of performance [7].

But all these efforts only address the purchased performance and are not related to the installed performance. The efficiency of air conditioning systems is directly related to the temperature at which it supplies cooling, and more importantly for these split units, the temperature at which it rejects the heat. The coefficient of performance (COP) is the ratio of the amount of cooling supplied to the electricity input into the cooling device. A typical chiller may have a COP of 3, delivering 3 kW of cooling for each 1 kW of electricity. But although this is often reported as a single value, it depends on the actual temperatures experienced by the system. Based on the LowEx building design paradigm [8] we focus on this temperature optimisation and recognize its significant influence on performance. This has led to the development of many new building systems in Switzerland [9,10], which can achieve better performance through a whole system evaluation that minimises temperature differences, allowing COPs higher than 10 [11].

Now we aim to achieve a similar optimisation for cooling systems in the tropics in our high temperature cooling system laboratory [12]. For split unit systems we must address the way in which they reject heat into the environment, because installation methods can significantly affect the temperature and therefore the actual performance. Finding the lowest possible temperature to reject the heat will deliver the highest performance, but we have evaluated the climate of Singapore, and there is little temperature variation that would provide better potential than the air as a heat sink [13]. Therefore it is essential to install the split unit systems in a way that take advantage of the coolest air temperature possible. Unfortunately standard practice overlooks the importance of this objective, and by looking at Fig. 1 it is clear how non-ideal higher temperatures may be generated around the units.

Few people enjoy the aesthetic of split type units hanging on façades as shown in Fig. 1. As a result they are often installed in spaces that are hidden from view, in recess spaces or in confined spaces such as inner light wells. Unfortunately, those spaces are often sheltered from wind to carry away the rejected heat. A *stack effect* is a possible consequence: The heat rejected from the condensing units induces a vertical, buoyancy-driven airflow, creating an increasingly hotter air bubble that rises up along the building. The condensing units further up have to reject heat to this hotter environment, and will thereby operate at reduced performance or, in extreme cases, may stop working if the working fluid cannot reach the necessary temperature any more.

A number of studies have been conducted, using CFD simulations to analyse the phenomenon, with Bojic reviewing the extensive CFD simulation studies on high-rise buildings in Hong Kong [14]. Chow argued that computer simulation was the most convenient and economical way to study the stack effect and found that the condenser on-coil temperatures rise more than 7 K for the top floors, for a high-rise residential building in Hong Kong [15]. In following studies, Chow and Bojic analysed the effect of the building re-entrant shape on the stack effect [16,17]. Bojic found the on-coil temperature increase by 4–9 K on the 30th storey, depending on the rejected heat per condensing unit (2–6 kW) [18]. Priyardarsini observed that the on-coil temperatures rise up to 38 °C for Singapore, when subject to wind flows perpendicular to a narrow urban canyon [19]. Choi analysed the situation where the condensing units are installed in an air-conditioning plant room. They found that the stack effect depended considerably on wind speed and wind direction. While moderate strength wind from the side lead to an increase of less than 2 K, frontal winds caused an increase of the on-coil temperature of 6 K over 40 storeys [20].

Chow [16] introduced the Condenser Group Performance Indicator (CGPI) that describes the average percentage drop in COP of a group of air-conditioners compared to the performance under a reference on-coil temperature T_{ref}. In that study, the performance drop was 9.4 to 25.5%, depending on wind and the shape of the re-entrant area where the condensing units were located. Choi [20] found values for CGPI between 5.07 and 22.25 for different wind speeds and direction.

What is missing are measured data that confirm, reject or alter the findings from the simulation studies. The only laboratory experiments we are aware of were conducted on a model in the scale 1:100, representing a 41-storey building, to measure the stack effect from water heaters in the inner light well [21]. While the aim was to study the natural ventilation characteristics for the removal of pollutants, it was used to test CFD models to study the stack effect from condensing units [22]. There are a variety of reasons that measured data from actual buildings is not available including the difficulty in setting up the measurements, the scale of the

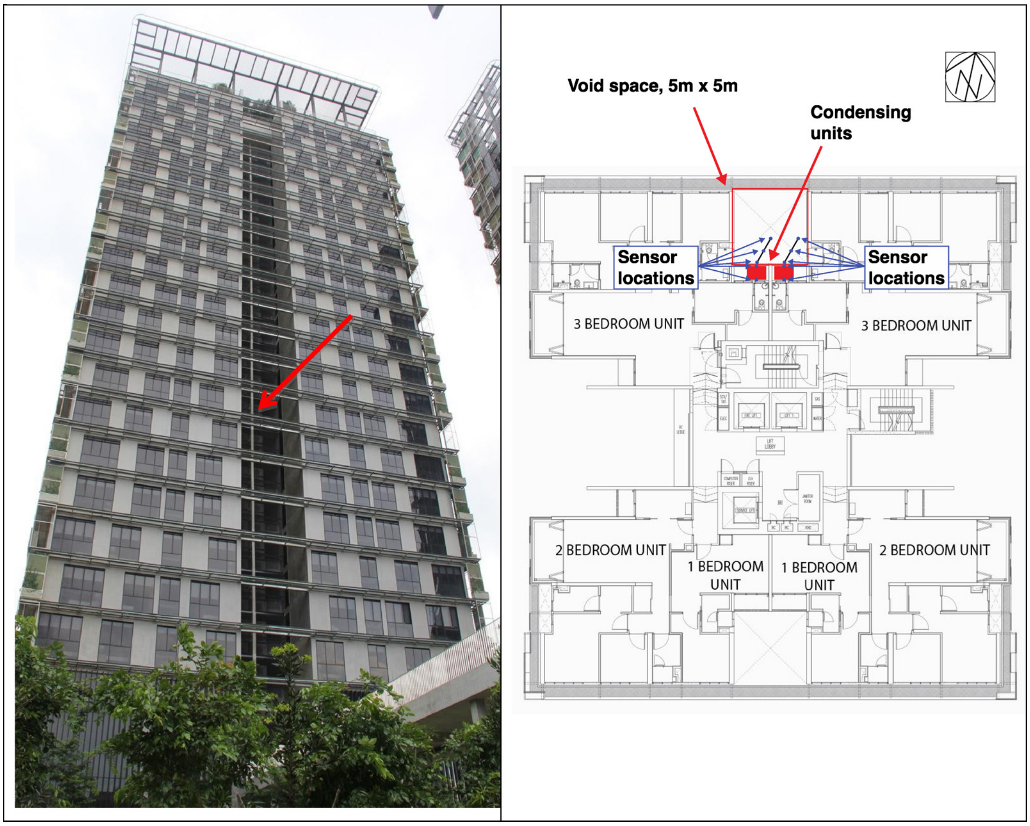

Fig. 2. Kent Vale II building with the studied void space – photo and plan.

outside space of a high-rise building, and most importantly gaining access throughout the vertical spaces that are typically occupied by private residences.

This study fills this gap with measurements from a building in Singapore, using recent sensor technology that allows a much simpler measurement setup, and could be implemented in the short time frame between building completion and occupancy. The aim was to measure in a real 24 story residential tower if there was indeed a measurable stack effect and if yes, how large it would be.

2. Methodology

2.1. Case study object: Kent Vale II

The measurements were conducted at Kent Vale II (Fig. 2), a housing block at the National University of Singapore that were completed in 2012 [23]. The analysed building has 24 storeys, with 4–6 apartments per floor, amounting to total building height of 84 m. We investigated the void space of 5 × 5 m on the northern side along the entire building height. The two adjacent 3-bedroom-apartments reject the heat from air-conditioning into this void space, through each 3 condensing units placed on AC ledges of 1.0 m depth, with an overall installed cooling capacity of 21.1 kW. The average rated efficiency of the air-conditioners is a COP of 3.2. The bottom 4 levels on this side of the building are void decks, without apartments.

This vertical void space is a typical feature of Singapore's residential building style: it increases façade area, window openings and allows hiding the condensing units in this recessed space. In this case, the building designers additionally installed full height view screens in front of the AC ledges, louvres consisting of vertical metal strips that are turned 30° to the side, completely shielding the condensing units from view unless standing exactly in line with the louvres (see Fig. 3). Horizontal sunshades made of steel circumvent the entire building.

2.2. Sensor deployment and measurement setup

The aim of the measurements was to produce an accurate understanding of the buoyance driven airflow in the void space and to measure the influence of this temperature stratification on the operation of the condensers. Sensors were therefore installed at regular intervals along the entire height of the building, every 5th floor to capture the vertical temperature stratification. Sensors placed at different distances from the condensing units would generate the horizontal temperature distribution to establish an understanding of the 3-dimensional temperature distribution. Bojic [18] showed that the thickness of the vertical air stream varies depending on the amount of rejected heat. Based on his results, we estimated that sensors placed in up to 2 m distance would capture the extent of the vertical air stream and detect in what distance from the condensing unit the effect rising air bubble will stop. In overall, three temperature sensors installed in the void space at each level, the first temperature sensor at short distance (0.2 m), in front of the condensing units, and the second and third sensors in the distances 1.0 m and 2.0 m respectively.

One of the reasons that nobody had collected temperature data in this void space before was the difficulties involved with installing sensors at this large scale, including the cabling to and from all sensors. The sensors are employed as a distributed wireless communication chain, facilitating the data transmission across the large vertical distance with minimal infrastructure. The sensors used in this experiment are digital humidity and temperature sensors SHT11 that sit on TelosB TPR2420 wireless nodes, recording a data point with dry bulb temperature and relative humidity while calculating dew point temperature every 2 s [24]. These wireless nodes

Fig. 3. Condensing units with louvres: split units visible (left) and hidden from view (right).

run with TinyOS, a small, open-source software operating system that supports large scale, self-configuring sensor networks [25]. The wireless nodes running the Collection Tree Protocol (CTP) to self-configure into a sensor network that enable the collection of measurement values without a single cable being laid; the last node will connect to a laptop to store the data [26].

We installed sensors on the eastern side of the void space at every 5th level (see Figs. 4 and 5) – floors 5, 10, 15, 20 and 24. 3 sensors were placed into the void, hanging off a 2 m long pole, in front of the condensing units. These sensors were protected from rain using plastic cups. 1 sensor was placed at the air intake of the condensing unit, measuring on-coil temperature, and 1 sensor was placed at the air exhaust, measuring off-coil temperature. This setup would allow detecting the stack effect and its influence on the condenser temperatures. The same set of 5 sensors was installed on the western side of the void on level 15. This setup would show the temperature distribution in a horizontal slice of the void space and the air-conditioner ledges. A total of 33 sensors were installed.

To provide an additional check of temperature changes, we measured the surface temperature of the concrete walls in the void space with the handheld infrared thermometer, Testo 810, with an accuracy of ±2.0 °C over the range of −30 °C to 100 °C. It was also used to measure the temperatures of the coils of the split unit condensers and the fan coils of the evaporators.

2.3. Measurement process

The measurements took place on 23 November 2012, in the short period after the building had been commissioned but before people started moving in. The building and air-conditioning systems were fully operational and controllable with little interference from individual user behaviour; we had access to 38 of 40 apartments. After setting up the sensor equipment, we started the data collection with all air-conditioning equipment switched off. We then switched on all air-conditioners in all rooms across the entire height of the building. In the absence of any internal loads, from people, lighting or electronic equipment, 2 windows were left slightly open to prevent the air-conditioners from switching off completely once they reached their set temperature.

To detect a stack effect, two steady state situations are compared: OFF – when all air-conditioning equipment is switched off, and ON – when all equipment is switched on. In the first case, no heat is rejected from the condensing units, and the resulting temperature distribution should show the natural stratification in the outdoor space. In the second case, the temperature stratification due to mechanical heat rejection should be detected. For both cases, we chose a 30-minute-period of steady state conditions.

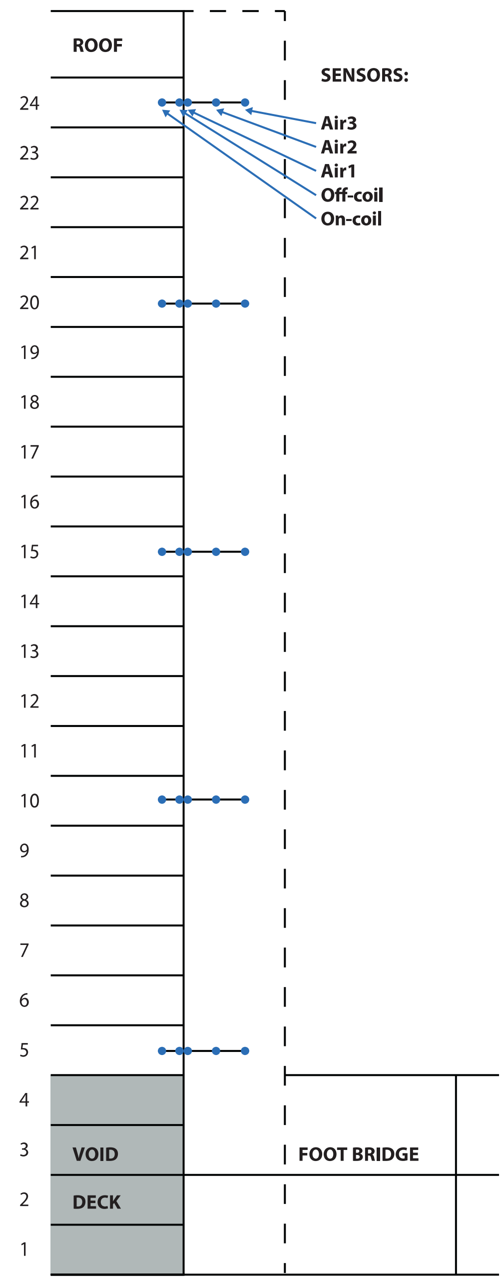

Fig. 4. Elevation drawing of measurement setup, wireless sensors Air1, Air2, Air3 placed in void space, sensors On-coil and Off-coil placed before and after condensing units.

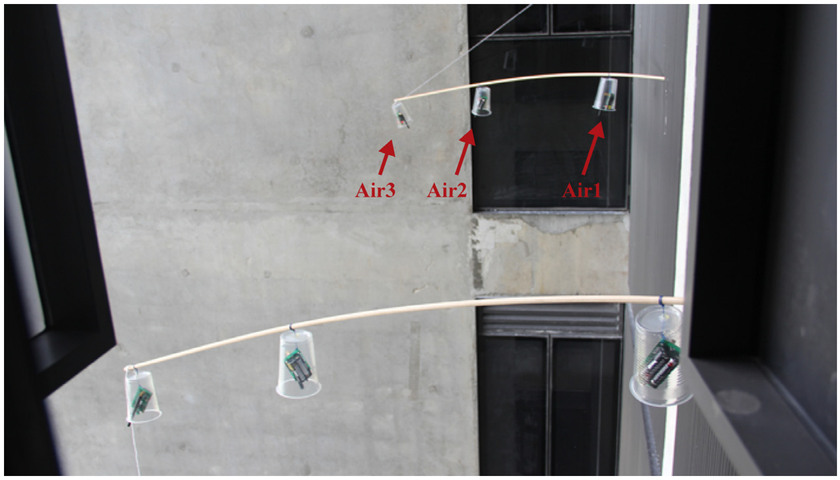

Fig. 5. Measurement setup, wireless sensors (Air1, Air2, Air3) placed in void space. At approximate 0, 1 and 2 m.

2.4. Energy performance calculations

The COP of the units was estimated in order quantify a direct effect on performance. The COP can be expressed as a fraction of the ideal Carnot performance of heat engines, representing machine inefficiencies by the exergetic efficiency (defined as g-value), typically ranging from 0.4 to 0.6:

$$COP_{\text{cooling}} = \frac{Q_c}{W} = g * \frac{T_1}{(T_2 - T_1)}$$

where Q_c is the heat removed, W is the work consumed by the chiller, g is the exergetic efficiency of the chiller, and T_1 and T_2 are the temperatures of the cold (building system) and the hot reservoir (environment).

We estimated the influence of different air temperatures, and therefore of different condensing temperature T_2, on the energy performance of the chiller using the above equation. The off-coil temperature is the relevant temperature for this calculation. We assumed that the condensing temperature is 2 °C above the off-coil temperature to account for imperfect heat transfer of the heat exchanger. For the OFF-state, measured on-coil and off-coil temperatures are the same; we thus used the same temperature increase that the air is subjected to when passing through the condenser heat exchanger as we measured for the ON-state. For the evaporation temperature T_1 we assumed 8 °C.

To qualify for the highest energy label for multi-split air-conditioners of the National Environment Agency (NEA), which is a prerequisite for Green Mark Platinum (highest rating) buildings, the COP for split units has to be at least 3.34 under rated conditions, i.e. 35 °C outdoor dry bulb temperature [7]. We used these rated conditions to calculate the g-value (exergetic efficiency) to fulfil minimum standards and used this for the calculation of the COP.

3. Results/discussion

3.1. Data overview

The period from 13:10 to 13:40 serves as the steady-state case for all equipment switched OFF, the period from 15:10 to 15:40 serves as the steady-state case for everything switched on. The ambient air temperatures and the lack of penetration of solar radiation into the recessed space were equivalent, making the comparison at different times acceptable. At 15:45, the effects of an incoming storm began to appear, rendering further measurements useless for the objectives of this study. These 30 min intervals were analysed to define an average value while noting the temperature variation that occurred, which was on the order of 2 °C.

Table 1
Wind speed and direction, average, minimum and maximum values: OFF vs. ON.

Data	Unit	Average	Minimum	Maximum
Wind speed – OFF	m/s	3.0	1.6	4.1
Wind speed – ON	m/s	5.8	3.8	6.9

4 out of 33 sensors failed to communicate with data logger during the field measurements. Due to external constraints, these sensor failures could not be corrected and have as a consequence left holes in the overall data picture.

General weather data for the duration of the measurements were available from a weather station of the NEA, at Pasir Panjang Terminal (1°16.941′ N, 103°45.270′ E) [27], 26 m above ground. The temperature data were only available as hourly values. The day of the measurements represents a typical day in Singapore, as can be seen from the comparison between the NEA data and statistical data for November [28] in Fig. 6, The average dry bulb temperature was 31.6 °C for the OFF-state and 30.3 °C for the ON-state. The latter value is influenced by heavy rain that began after 15:45, which resulted in a decrease to 25.7 °C for the subsequent hourly value. These values are similar to our temperature measurements at Kent Vale as well as to the weather station data collected by the Department of Geography at NUS [29]. The investigated void space is not influenced by solar radiation, as it is shaded for the entire day.

Wind direction and speed data, in 1-minute-timesteps, were quite regular. The average values, the minimum and maximum values recorded during the experiment phase are displayed in Table 1. The wind speed is a bit higher than for the average weather data of Singapore of 2.2 m/s. As can be seen, it was picking up in the time leading up to the storm that began after 15:45.

The prevailing wind direction, almost the same for both cases, is such that the influence on the experiment site is minimal (Fig. 7). The stack – oriented towards 350° – is on the opposite side of the building, which would limit fluctuations from turbulent conditions in the stack.

3.2. Stack effect

The sensors Air1, Air2 and Air3 are the ones placed into the air space directly in front of the condensing units, in line with the metal louvres (see Fig. 5). The change in the vertical temperature distribution in the void space for these locations is shown in Fig. 8. In the OFF-state, the temperature difference between floor 5 and

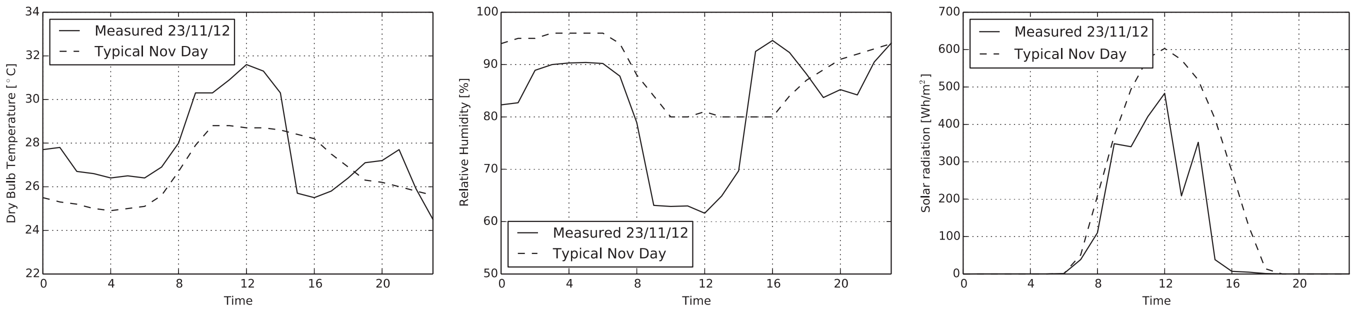

Fig. 6. Weather conditions on the day of measurements 23/11/12 compared to the average day for November [28]. Left: Dry bulb temperature [27]. Middle: Relative humidity [27]. Right: Solar radiation [29].

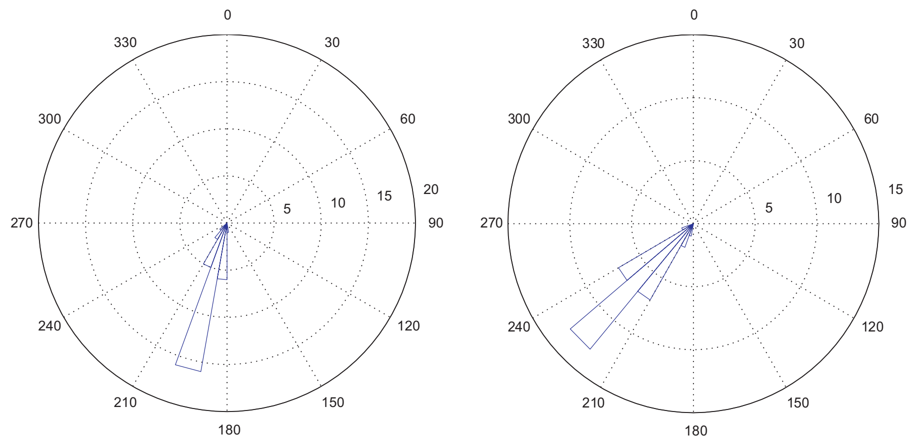

Fig. 7. Wind rose 1-min data [27] of status OFF from 13:10 to 13:40 (left) and status ON from 15:10 to 15:40 (right).

floor 24 for Air3 is less than 1 K. In the ON-state, the air temperature increases continuously towards the top of the building: While the temperature at the bottom is still 32.5 °C, at the top it reaches 54.2 °C directly in front of the condensing unit and 44.1 °C in 2 m distance. The temperature for the sensors Air2 and Air3 increases up to 12.7 °C above the ambient temperature at the bottom, which clearly shows the stack effect induced by the condensing units.

While the temperature directly after the condensing is considerably higher, there is not much difference between 1 and 2 m distance. For some data points, it is even hotter at the 2 m distances, suggesting complex air movements. The depth of the rising hot air stream appears to be larger than 2 m.

We also measured the surface temperatures of the three walls enclosing the void space. The results confirm the values found in the air temperature measurements, both regarding the absolute values and the temperature distribution in vertical direction. The values are slightly lower than the air temperatures; longer exposure of the concrete walls to the hot airstream might have brought the temperatures closer together.

In the OFF-state, only a small temperature difference of 1.1 °C is found between the level 5 and 24. In the ON-state, the surface temperature of both walls at the side, measured in approximately 2 m distance from the condensing units, increases continuously from 32.1 °C at the bottom to 39.6 °C at the top, corresponding to sensor Air3. The wall between the two sets of condensing units reaches a surface temperature of 48.8 °C at the top, corresponding to the sensor Air1, closest to the condensing unit.

3.3. Stuck effect

Additional to the effect of a rising hot air bubble, another unexpected effect was observed from the measurements, shown in Fig. 9 for level 15. The chart represents the temperatures distribution in horizontal direction, before and after the condensing unit and in the void space. The void space is separated from the condensing units by the louvres that hide them from view. The inlet temperature of the condensing unit is higher than the air temperature in the void, indicating that some of the hot air must be stuck behind the louvres is recirculated to the inlet of the condensing unit. The louvres therefore act not only in their design function as visual barriers, but unfortunately also as a barrier to airflows.

Another indicator for this stuck effect is visible in Fig. 10: Not all of the on-coil temperature increase can be attributed to the stack effect. There is a 9 °C difference between OFF- and ON-state also observed at level 5. This can only be due to the stuck effect since there is no condensing unit below that would account for an increase due to the stack effect.

3.4. Condensing temperatures

The main motivation for this study was the temperature distribution at the inlet of the condensing units to evaluate the influence of the stack effect on the performance of the air-conditioners. Fig. 10 represents the measured values at the inlet and outlet of the condensing units, representing on-coil and off-coil air temperatures. In the OFF-state, without heat rejection or induced air movement, temperature between 30.5 and 32.1 °C are measured for all sensors. In the ON-state, the temperatures increase significantly. The on-coil temperatures start at 39.5 °C at level 5 and rise up to 50.3 °C for level 10 and above. The off-coil temperature starts 50.5 °C and rises even up to 59.5 °C. The air temperature increases by a range of 7.5–11.8 °C across the condensing units as they reject heat, the average value is 9.0 °C.

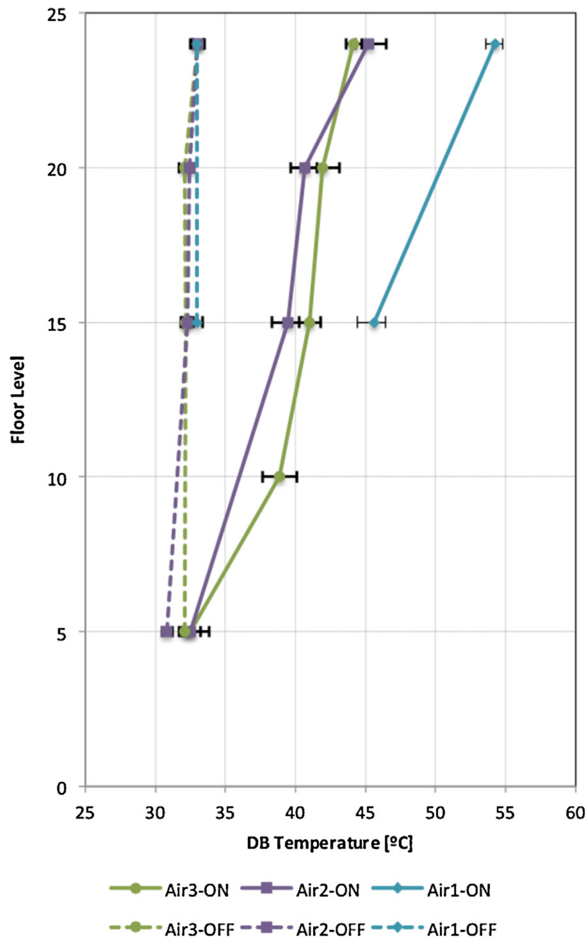

Fig. 8. Stack effect: air temperature distribution in recess space: OFF vs. ON.

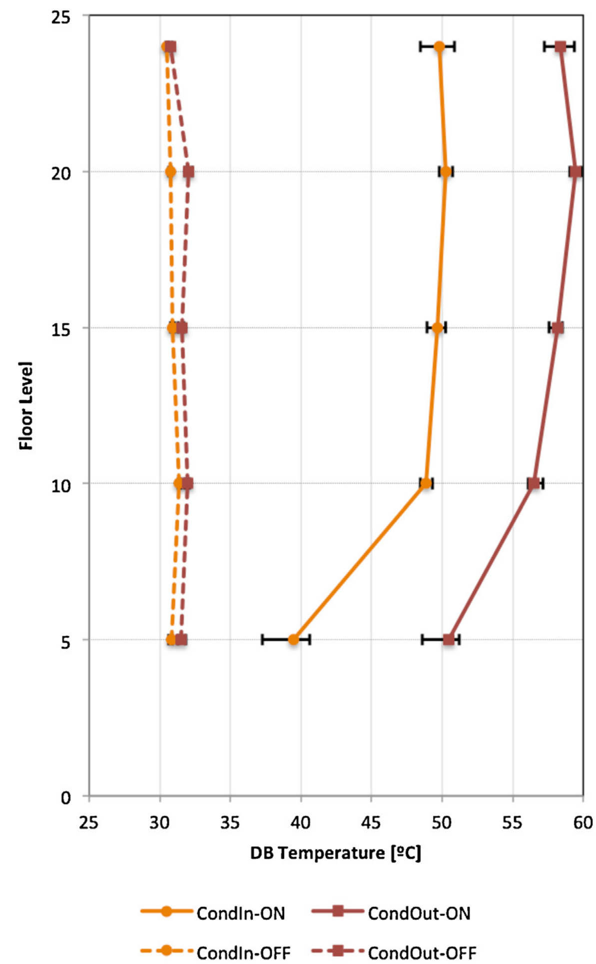

Fig. 10. Condenser temperature distribution, on-coil and off-coil temperature: OFF vs. ON.

The on-coil and off-coil temperatures are much higher than expected. None of the previous studies, that simulated the stack effect, predicted an increase of 19 °C, which is what was found for the on coil temperature over 20 storeys. Clearly, this is partially due to the unexpected stuck effect, but there is an obvious vertical increase of about 10 °C in the initial 5–15 storeys for the on-coil temperatures in Fig. 10, and there is a clear increase of 10–13 °C that occurs in the air of the void space shown in Fig. 8, both of which can be attributed to the stack effect. The maximum value found in literature was around 7 °C for a similar situation, so the experiments may demonstrate that the effect could be even more pronounced in reality than in models and simulation.

Looking at floor 5 in Fig. 10, we can say that around 10 °C temperature increase for the on-coil temperature can be attributed to the stuck effect alone, i.e. hot air that recirculates. When looking at the change from level 5 to 10, the further increase is probably solely due to the stack effect, i.e. hot air rising from the condensing units below. The relative importance of these two effects for levels higher up is difficult to evaluate. As suggested by Choi [20], the vertical airflow may make it harder for the fan to exhaust the hot air to the outside, an effect similar to the one we use in air curtains in building entrances. Even so, this would still be a side

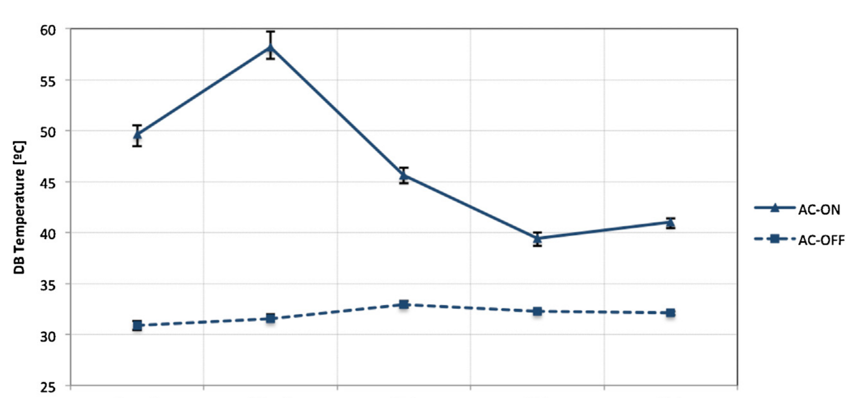

Fig. 9. Horizontal temperature distribution on level 15 before and after condensing unit and in void space, separated by louvres.

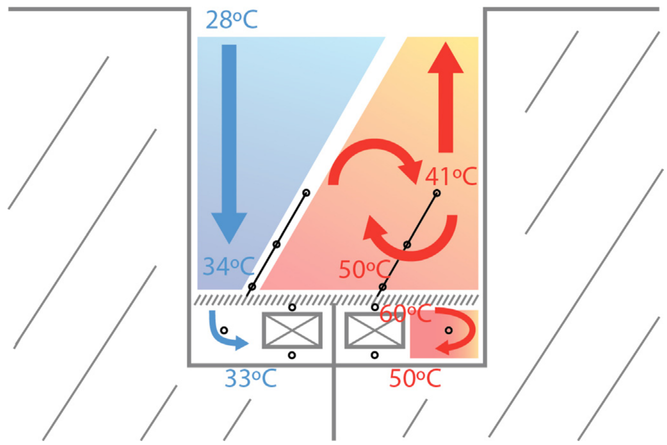

Fig. 11. Conceptionalisation of horizontal temperature distribution with indicated airflows on level 20.

effect of the buoyancy-driven airflow. Another factor could be the slightly elevated wind speed for the higher floors. There are many possible reasons why the temperature increase slows down and is levels out above level 10; this question will need to be studied in more detail. Generalising the results, we can broadly estimate that roughly 10 °C increase is caused by the buoyancy-driven rising hot air of the stack effect, and roughly 10 °C increase is from hot air being entrained from the barrier design causing am unexpected stuck effect.

On level 20, we installed the same measurement setup for the left set of condensing units to analyse the temperature distribution and the airflows in a horizontal plane. Fig. 11 shows a conceptualisation of the horizontal temperature and airflow distribution on level 20 based on all measurements: Some of the air leaving the condensing units on the right side passes through the louvres and accumulates on the right side, deflected by their 30° angle. The hot air bubble in this corner rises vertically to form the observed stack effect. Some of the air leaving the condensing units gets trapped behind the louvres, recirculates and further increases in temperature. On the left side, the measured on-coil temperature is 34.0 °C only, meaning that cold air flows in from outside the recess space. The horizontal temperature distribution can be expected to look similar at the other levels, albeit with different absolute temperatures, e.g. reaching 54.2 °C in the void space on the 24th level.

3.5. Energy performance

We estimated the influence of stack and stuck effect on the performance of the air-conditioner across the height of the building. As outlined in Section 2.4, we used 8 °C as the evaporator temperature T_1 and the off-coil temperature plus 2 °C, resp. on-coil temperature plus 9 °C (average temperature increase across heat exchanger) plus 2 °C, for the condensing temperature T_2. The temperatures of the heat exchangers for the split units, measured by the infrared thermometer, were found to be 8.9 °C at the supply to the evaporator fan coil, and 34.9 °C for the on-coil side of the condenser heat exchanger surface in operation, compared to 27.3 °C for condenser not in operation, which verified our assumptions well enough.

Based on rated conditions we calculated the *g*-value (exergetic efficiency) to be 0.45 to fulfil minimum standards. The internal efficiencies of the actual equipment will vary slightly, but are generally constant over the normal operating range. Even though the exergetic efficiency probably degrades at the highest on-coil temperatures we observed, we assumed constant exergetic efficiency. This allowed us easily to evaluate the effect of increased temperatures on the chiller performance.

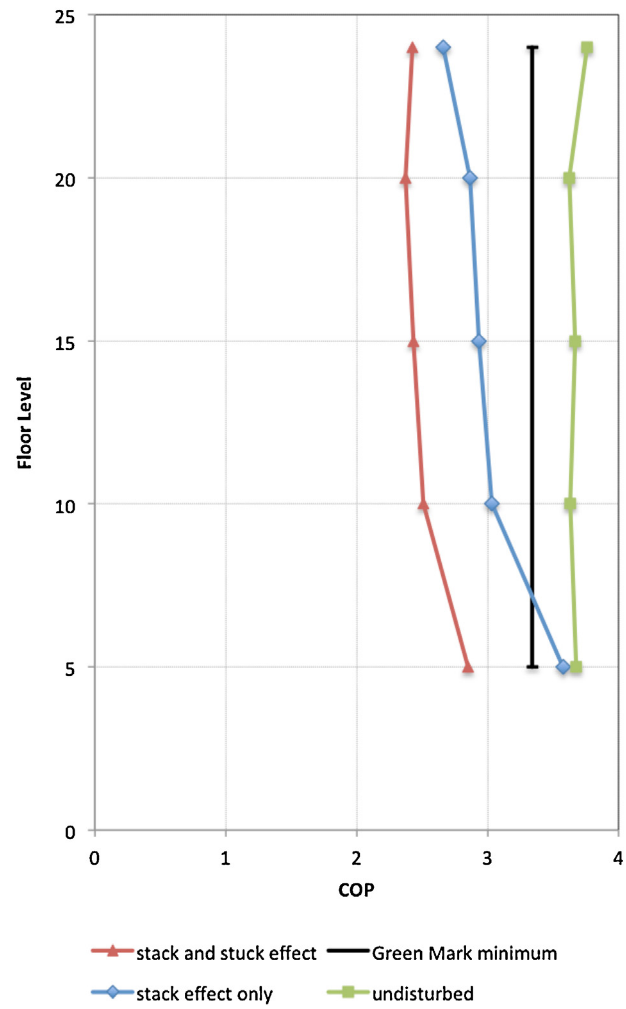

Fig. 12. COP for all floors with rated conditions as a function of the condensing temperatures, influenced by stack and stuck effects: OFF vs. ON.

The COP for the different storeys is shown in Fig. 12 for three cases based on our observed temperatures: (1) the undisturbed design case, (2) when subject to the stack effect only and (3) when subject to the combination of stack and stuck effect. There is a significant reduction in the COP for all air-conditioners but more prominent for the upper levels. Using the CGPI suggested by Chow [16], i.e. the average percentage drop in COP for all air-conditioners, the performance of decreases by 18% due to stack effect only and by 32% due to combined stack and stuck effect, compared to the undisturbed design case as reference.

It is clear that the efficiency of the air-conditioners do not only depend on their internal efficiencies, and what is written on the label when they are purchased, but also on design decisions regarding how they are installed in the building. To achieve higher system efficiencies, the system temperatures, i.e. the temperature lift between evaporator and condenser, need to be taken into account. Thermodynamic laws set an upper boundary of the maximum performance that may be achieved. To arrive at LowEx systems with COP exceeding 10 [11], an analysis of the whole-system including the different operation temperatures is needed.

3.6. Error analysis and limitations of the study

The manufacturer TelosB sensors guarantees an accuracy of ±0.5 °C at 30 °C and ±1.3 °C at 60 °C. Before the measurements, all sensors were calibrated at 30 °C using PT100 tenth-DIN sensors with ±0.03 °C accuracy at 0 °C before starting the measurements.

For the charts we chose to represent the minimum and maximum values measured for each data point instead. Those variations are small and in a similar order of magnitude as the sensor accuracy. There is a clear difference between the two steady states. The variation is much larger for ON, an indicator for the more dynamic conditions with regard to airflow and temperatures.

The decision to switch on all air-conditioners at the same time, and even opening windows may seem excessive. The total cooling demand is certainly at the upper bound of what may occur in operating the building; it has to be considered a worst-case scenario. In the absence of knowing if a stack effect may actually be discerned, the aim was to detect the stack effect in the first place. This influence will be further investigated using a second dataset with variations of operational conditions.

The studied building is a typical residential building, with regard to the design of the void space as well as to the exclusive use of air-cooled split units. Industrial and commercial buildings often have either larger units not placed as regularly above each other or centralised cooling systems with cooling towers.

3.7. Design alternatives

It is important to understand that the Kent Vale II building is not badly designed but represents the top end of current design practise that earned Green Mark Platinum certification [6] and received the RIBA Awards of the year 2013. The architectural design fulfils expectations, providing sufficient space for the installation of the condensing units and hiding them aesthetically, additional to many other energy-related design criteria. The engineering design fulfils expectations, providing sufficient cooling capacity and choosing top-end equipment with highest efficiency ratings. There is no problem with the individual installation of the systems or the design of the building that has been built, but the process through which the building and its systems were separately considered has led to a degradation of performance that takes place unbeknownst to the designer involved. This is a problem that is the case with the installation air conditioning systems all over. A new design paradigm is needed that incorporates different fields of knowledge, including the relevance of system temperatures, to form integrative high-performance systems.

The aesthetically driven installation of louvres contributes to half of the temperature increase and therefore to the decrease of the chiller performances. The gaps between the metal sheets are so small that the airflow through them is seriously restricted and the angled direction can cause a build-up of hot air in one corner. Louvres that allow air to flow through more easily may not have so large an effect. While it may be possible that their influence becomes negligible, they will certainly not positively influence the performance of the air-conditioning system.

Hiding the condensing units behind louvres and at the back of a recessed void space is a design decision not informed by the system consequence. The experimental confirmation of both our hypothesis and the predictions in previous work [16,17] will provide valuable information that can be utilised for improved integrated system design methods in the future. The previous work can also build on this experimental data to extend and refine their analysis. The observed stack effect may however only be prevented by exposing the condensing units to wind movement that sufficiently disperses the rejected hot air or by spatially separating intake and outlet of air.

In the tropical environment of Singapore, there are no heat sinks of significantly lower temperatures that may be utilised for an increased chiller performance. All heat sinks – air, ground and water bodies – are in the same range as the air temperature [13]. The best potential represents the wet-bulb temperature of air through the use of evaporative cooling towers. While small-scale cooling towers have been investigated experimentally [30], only large-scale cooling towers make economical and operational sense. Heat rejection for high-performance buildings therefore needs a centralised system, as often used in combination with large centralised chillers. We have investigated an alternative solution where decentralised chillers – like standard split-type condensing units but water-cooled – plug into a centralised, water-based heat bus system that connects to the evaporative cooling tower [31,32]. Heat can be rejected at advantageous conditions while benefitting from the decentralised nature of the split systems. Instead of being subject to detrimental microclimatic effects like the ones studied here in this paper, the heat is rejected at the best possible location at better microclimatic conditions.

4. Conclusion

The main aim of this study was to experimentally evaluate the stack effect induced by the heat rejected from split type air-conditioners, an effect that in previous studies has only been analysed with CFD simulations. We have measured and shown for the first time that there is a significant stack effect from condensing units in a residential high-rise building in Singapore. The air temperature in the recess space increased continuously to reach up to 12.7 °C higher temperatures than undisturbed conditions at the top of 20 floors when air-conditioners were switched on.

Additionally we detected a significant stuck effect from hot air discharged from the condensing unit that gets trapped behind louvres acting as view barriers and recirculates back to the inlet of the condensing unit. The inlet temperature increases by 9.0 °C on the lowest level alone because of this effect. The two effects are more difficult to separate on higher levels but result in maximum measured values of 50 °C at the inlet and 59 °C at the outlet of the condensing units.

We calculated that these higher temperatures significantly reduce the COP of the air-conditioners by up to 18% due to the stack effect and up to 32% due to the stuck effect, increasing the operational costs of the building in ways that are not predicted or observed in standard design practice. The study shows that even very efficient chillers at rated conditions cannot exceed a certain overall performance. The achievable performance is limited, based on the second law of thermodynamics, by the system temperatures. Building designers very rarely consider this fact. For high-performance systems, a new integrated design paradigm is needed that considers the overall system.

While not all conditions, e.g. operational conditions could be accurately measured, the study proves for the first time the extent of these microclimatic effects and that they cannot be neglected for the design of energy-efficient buildings. The data may be used to validate and refine the CFD simulations to extend the knowledge and application of that valuable tool beyond this case study. There is a need to evaluate more dynamic conditions to evaluate the effects under different operational and environmental conditions. It is also not yet clear how stuck and stack effect influence each other. The understanding of these are necessary to draw valuable lessons for the design of energy-efficient buildings. A second set of data has been collected with more variation in operational parameters of the different split units, and will be presented in future work with expanded analysis and validation.

Acknowledgements

Special thanks to the NUS Office of Housing Services, Mr LEE Weng Fatt, for the opportunity and access to conduct measurements, and to the Kent Vale II facilities team, Mr LEE Peng Chuan and Ms TOH Gui Luan, for the support during the measurements.

A cordial thank you to Professors THAM Kwok Wai, Chandra SEKHAR and CHEONG David Kok Wai from the National University of Singapore for their support of the work.

Special thanks also to Professor LI Mo from the Nanyang Technological University for the support concerning sensoring and data collection.

This work was established at the Singapore-ETH Centre for Global Environmental Sustainability (SEC), co-funded by the Singapore National Research Foundation (NRF) and ETH Zurich.

References

[1] E. Mazria, Meeting the 2030 challenge through building codes, Arch. 2030, 2008.
[2] NEA, Singapore's second national communication. Under the United Nations framework convention on climate change, National Environment Agency (NEA), 2010.
[3] Department of Statistics, Report on the Household Expenditure Survey 2007/08, Singapore, 2009.
[4] United Nations Environment Programme (UNEP), Montreal Protocol On Substances that Deplete the Ozone Layer: 2006 assessment report of the Technology and Economic Assessment Panel, United Nations Environment Programme, Ozone Secretariat, Nairobi, Kenya, 2007.
[5] BCA, 2nd Green Building Masterplan, Building and Construction Authority (BCA), Singapore, 2009.
[6] BCA, The BCA Green Mark – Certification Standards for New Buildings (GM Version 4.1), Building and Construction Authority, 2012.
[7] National Environment Agency (NEA) Singapore, The Tick Rating for air-conditioners, 2013, http://app2.nea.gov.sg/energy-waste/energy-efficiency/household-sector/tick-rating
[8] H. Leibundgut, LowEx Building Design for ZeroEmission Architecture, 1st ed., vdf Hochschulverlag AG, Zurich, Switzerland, 2013.
[9] H. Leibundgut, Sol2ergie: System for ZeroEmission Architecture, 2012.
[10] F. Meggers, V. Ritter, P. Goffin, M. Baetschmann, H. Leibundgut, Low exergy building systems implementation, Energy 41 (2012) 48–55.
[11] I. Wyssen, L. Gasser, B. Wellig, M. Meier, Chiller with small temperature lift for efficient building cooling, in: Proc. Clima 2010, REHVA, Antalya, Turkey, 2010.
[12] M. Bruelisauer, K.W. Chen, R. Iyengar, H. Leibundgut, C. Li, L. Mo, et al., BubbleZERO-Design, construction and operation of a transportable research laboratory for low exergy building systems evaluation in the tropics, Energies 6 (2013) 4551–4571.
[13] M. Bruelisauer, F. Meggers, H. Leibundgut, Choosing heat sinks for cooling in tropical climates, Frontiers of Architectural Research 2 (2013) 292–300.
[14] M. Bojic, S. Savic, D. Nikolic, Application of computational fluid dynamics to flow next to high-rise buildings in Hong Kong due to air-conditioner heat rejection, International Journal of Energy Technology and Policy 6 (2008) 159–177.
[15] T. Chow, Z. Lin, Prediction of on-coil temperature of condensers installed at tall building re-entrant, Applied Thermal Engineering 19 (1999) 117–132.
[16] T. Chow, Z. Lin, Q. Wang, Effect of building re-entrant shape on performance of air-cooled condensing units, Energy and Buildings 32 (2000) 143–152.
[17] M. Bojic, M. Lee, F. Yik, Influence of a depth of a recessed space to flow due to air-conditioner heat rejection, Energy and Buildings 34 (2002) 33–43.
[18] M.L. Bojic, F.W. Yik, M. Lee, Influence of air-conditioning exhaust on exterior recessed space, Building Research & Information 31 (2003) 24–33.
[19] R. Priyadarsini, N.H. Wong, K.W.D. Cheong, Microclimatic modeling of the urban thermal environment of Singapore to mitigate urban heat island, Solar Energy 82 (2008) 727–745.
[20] S.-H. Choi, K.-S. Lee, B.-S. Kim, Effects of stacked condensers in a high-rise apartment building, Energy 30 (2005) 968–981.
[21] H. Kotani, R. Satoh, T. Yamanaka, Stack effect in light well of high rise apartment building, in: Proc. IIR Int. Sym. Air Cond. High Rise Build. 97, 1997, pp. 628–633.
[22] T. Chow, Z. Lin, Q.-W. Wang, Applying CFD simulation in analysing split-type air-conditioner performance at buildings, Architectural Science Review 43 (2000) 133–140.
[23] NUS Office of Housing Services, 2013, http://www.nus.edu.sg/ohs/
[24] TPR2420 Wireless Sensor Network Nodes, 2013, http://www.memsic.com/wireless-sensor-networks/TPR2420
[25] P. Levis, S. Madden, J. Polastre, R. Szewczyk, K. Whitehouse, A. Woo, et al., Tinyos: an operating system for sensor networks, in: Ambient Intelligence, Springer, 2005, pp. 115–148.
[26] O. Gnawali, R. Fonseca, K. Jamieson, D. Moss, P. Levis, Collection tree protocol, in: Proc. 7th ACM Conf. Embed. Networked Sens. Syst., 2009, pp. 1–14.
[27] National Environment Agency (NEA) Singapore, Singapore's Climate Information – Data, 2013, http://app2.nea.gov.sg/weather-climate/climate-information/singapore%27s-climate-information-data
[28] ASHRAE, International Weather for Energy Calculations (IWEC Weather Files), 2001.
[29] NUS Department of Geography, Geography Weather Station – National University of Singapore, 2013, https://inetapps.nus.edu.sg/fas/geog/
[30] S.S. Hu, B.J. Huang, Study of a high efficiency residential split water-cooled air conditioner, Applied Thermal Engineering 25 (2005) 1599–1613.
[31] M. Bruelisauer, F. Meggers, R. Engler, H. Leibundgut, Heat bus for the tropics – exergy analysis of coupling decentralised chillers with central cooling towers, in: Proc. Clima 2013 Energy Effic. Smart Heal. Build., Prague, Czech Republic, 2013.
[32] M. Bruelisauer, S. Berthold, G. Aschwanden, I. Belle, E. Ostertag, F. Meggers, Reclaiming backlanes – addressing energy efficiency, outdoor comfort and urban space, in: Proc. SB13 Singap., Research Publishing, Singapore, 2013.