EVALUATING GROUP PERFORMANCE OF RESIDENTIAL AIR-CONDITIONERS

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ABSTRACT

The provision of split-type air-conditioners in high-rise residential building is very common in Hong Kong. So far the building re-entrant is the most popular place to accommodate the outdoor condensing units. In many cases, the heat dissipation from the outdoor units results in very unfavorable condenser working temperature. Predicting the thermal environment at a re-entrant is difficult because of the continuous changes in user demand and climatic condition. An energy performance indicator known as Condenser Group Performance Indicator (CGPI) is suggested to evaluate the air-conditioner operation. This paper discusses how the CGPI approach simplifies the complex situation by a numerical model using steady state fluid flow and thermal analysis, and makes use of a single parameter to compare different building design and equipment layout schemes. The effect of equipment random operation is also examined in this paper.

1. INTRODUCTION

The use of split-type air-conditioners is common in private residences of Hong Kong. In the form of either single or multi-split units, the split-type air-conditioners typically serve bedrooms, living/dining rooms, and in some cases, kitchens. The distinct advantages of split-type air-conditioners lie in the quiet operation and the flexibility in multi-room services. These are achievable by inter-connecting the outdoor unit (that houses the compressor, condensing coil and associated cooling fan etc.) with one or more indoor units (each including the DX cooling coil, expansion device, supply fan etc.). Heat dissipation at the condensing coil allows the “pumping” of heat energy from the air-conditioned space to the open space through the refrigeration circuit. For low-rise houses, the outdoor units can be placed at the roof, or at the backyard. For high-rise apartment buildings however, for aesthetical reason, building re-entrant – a recessed space between two neighbouring apartments – is by far the most popular place to accommodate the outdoor units. Fig. 1 shows one high-rise residential development with 11 residential towers (T1 to T11) and a resident garden/club-house at the podium level. Underneath the podium are the car park and the shopping mall. Apartments at a residential tower radiate outward from the building core with four re-entrants formed between adjacent apartments.

A typical arrangement of outdoor units at a building re-entrant is given in Fig. 2, where A to F labelled their positions. In architectural design, a re-entrant serves as an open space where the kitchens receive daylight and ventilating air. The presence of these air-cooled condensing units however introduces a thermal problem - the thermal buoyance as a result of heat dissipation leads to the development of a rising air plume; inadequate air exchange at this recessed space elevates the ambient temperature, and the insufficient cooling significantly affects the condenser performance, especially for those at the upper floor levels. The result could be an overall degradation of the capacity and the efficiency of the air-conditioners of the entire building re-entrant. As most condensing units are unlikely to function properly at an on-coil temperature (supply cooling air temperature) above 45°C for an extended period, the problem is therefore not only energy wastage but also equipment malfunction [1]. Similar problems occur in window-type air-conditioners when they are placed at the building re-entrant and this was studied by Bojic et al. [2].

During the air-conditioning design stage, the design engineer has to ascertain that these condensing units will work properly under foreseeable operating conditions. This may not be an easy task since the working conditions of the air-conditioners in a group are highly interactive. In a residential building (that is unlike an office building), there is no fixed usage pattern of the air-conditioners. The climatic conditions (like the wind breeze) are always changing. The airflow pattern at a re-entrant is unsteady and unavoidably complex. The prediction of the air-conditioner performance has
been in most cases handled by a simulation specialist, who works on a computational fluid dynamics (CFD) program using a series of simplifications to investigate into an assumed worst operating condition. A project client is likely pleased by the prediction that the on-coil temperature will not exceed the alarming 45°C. The loss in efficiency of the air-conditioners as a whole may not be a main concern of the project team. This attitude can have a significant impact on building energy performance and sustainability. According to the Hong Kong Government energy statistical data [3], the consumption of electricity in the domestic sector had been increased by 100% in the 10-year period from 1988 to 1998. A brief analysis of the seasonal data revealed that more than one-third of the domestic demand had been for air-conditioning purposes.

Fig. 1: Plan view of a residential development in Hong Kong

Fig. 2: Floor plan showing outdoor units at a building re-entrant
2. ENERGY PERFORMANCE EVALUATION

2.1 EER And COP

Energy performance of a room air-conditioner can be described by the Energy Efficiency Ratio (EER), which is a ratio of the cooling capacity in Btu/h to the electricity consumption in Watt, measured at the standard rating condition [4]. The higher the EER, the more energy efficient the unit is. Alternatively, a dimensionless term “Coefficient of Performance” (COP) can be used, which in a broader sense is defined as a ratio of the unit cooling capacity to the overall power input. The overall power includes the electricity consumption at the compressor, the fans at both indoor and outdoor units, and all auxiliary devices. The COP of a split-type unit varies with the unit working conditions, for instance, the room air condition and the condenser cooling condition.

In a high-rise apartment building, not all air-conditioners are in service at any particular moment. For those in operation, the thermal loads do vary dynamically. On the other hand, the airflow and temperature distributions within a re-entrant are influenced not only by the equipment operation conditions but also by the climatic conditions such as outdoor temperature and wind. These factors have made the problem analysis via field measurements or practical experiences gained from existing building projects uneconomical and inconclusive. In order to have a practical, systemic and consistent evaluation, an energy performance indicator called Condenser Group Performance Indicator (CGPI) has been derived and found to be very useful in comparing different design schemes. This is briefly described below.

The coefficient of performance (COP) of a split-type air-conditioner is a function of the room air temperature (T_r) and the condenser on-coil temperature (T_o). At a fixed T_r, it has been shown that COP varies linearly with T_o, i.e.

\[ \text{COP}_{T_r} = a - bT_o \]  

where a and b are positive constants. At a desirable room temperature, say 25°C, a derivation from manufacturing data gives the following linear regression representation [5]:

\[ \text{COP}_{25} = 5.153 - 0.0738T_o \]  

The equation applies for the range of T_o from 25 to 45°C. Hence when T_o increases from 33°C (which is the summer design condition of Hong Kong) to 45°C (which is the condenser normal operation limit), the COP decreases from 2.718 to 1.832 if the room temperature remains at 25°C. The loss in COP is about one-third (32.6%).

2.2 Group Performance

When a number of air-conditioners are placed close together, the condenser heat dissipation will affect the energy performance of all air-conditioners in the group. The accommodation of condensing units at a building re-entrant is one typical example. The Condenser Group Performance Indicator (CGPI) can be used to evaluate the energy performance of say “n” number of air-conditioning units working together. This term describes the average percentage drop in COP of all “n” numbers of air-conditioners. By definition, for any referenced condenser on-coil temperature T_ref and room temperature T_r,

\[ \frac{100}{n} \sum_{i=1}^{n} \left[ 1 - \frac{\text{COP}_r \left( T_{o_i} \right)}{\text{COP}_r \left( T_{o_{ref}} \right)} \right] \]  

T_ref can be an arbitrarily assigned outdoor temperature, say the summer design condition 33°C. By manipulating with equations (2) and (3), the corresponding CGPI expression for T_r = 25°C and T_ref = 33°C is given by:

\[ \text{CGPI}_{25}(33) = \frac{76.89T_{o_{ref}} - 72.2}{T_{o_{ref}}} \]  

where T_{o_{ref}} is the mean condenser on-coil temperature of all air-conditioners. When T_{o_{ref}} is the same as T_ref (equal to 33°C in this case), equation (4) shows that the group effect diminishes and CGPI has a zero value. If all on-coil temperatures reach the 45°C limit (hence T_{o_{ref}} equal to 45°C), CGPI is 32.6%, i.e. the overall drop in COP is one-third and this matches the analysis in Section 2.1 above.

Hence if the on-coil temperature of the individual condensing units can be determined, e.g. via CFD simulation, then the overall energy performance of the arrangement can be assessed by the corresponding CGPI value. It should be noted that CGPI can serve for the design comparison purpose by using simple assumptions in equipment operation even if they are not entirely realistic (for instance assuming 100% equipment operation). Under the same assumptions, the design scheme with a lower value of CGPI is a better design. This concept will be further elaborated in the following sections.

2.3 Numerical Computation

Simplifications and assumptions are to be adopted in developing a steady-state computational model for the CGPI analysis. These include:

- All outdoor units are in operation.
The outdoor units are identical, having the same cooling fan model and the same steady heat dissipation rate.

All wall surfaces of the re-entrants are flat, and without window openings for possible indoor-outdoor air exchange; in particular the effects of kitchen and toilet exhausts are neglected.

There is no wind to disturb the airflow.

The heating effect of solar radiation on the solid surfaces is negligible.

Outdoor temperature and air movement remain steady.

In the following section, the findings of various comparative studies concerning building geometry are summarized. These are important information to the building designers. In our work, CFD simulations were performed using the CFX 4.2 software [6] with the standard k-ε turbulent model and applying Boussinesq approximation to non-uniform rectangular grids [7]. Condensing units were modelled by adding volumetric heat sources and body forces to the cells enclosed by four thin surfaces, leaving two opposite vertical openings for the cooling air passage. Detailed description of the technique including the validation work can be found in Chow et al. [8].

3. EFFECT OF BUILDING GEOMETRY

3.1 Building Height

High-rise apartment buildings are everywhere in the urban districts of Hong Kong. Some new residential projects at the city centre are designed for 60 floor levels or more. The condenser heat dissipation problem is expected greater at taller buildings, where more outdoor units are installed and the temperature effect is accumulating at the rising air plume.

The natural upward airflow rate at a re-entrant depends on the thermal buoyance that works against the mechanical friction loss along the flow path, including the pressure loss due to the condenser fan churning effect [9]. The thermal buoyance increases with the air temperature difference $\Delta T$ between the inside and outside of the re-entrant. On the other hand, $\Delta T$ decreases at a higher airflow rate if the heat dissipation rate remains the same. Hence the relation between the temperature elevation and the overall building height is not directly linear. Fig. 3 shows the typical pattern of variation of CGPI with the overall height of a building, assuming the same outdoor unit arrangement at all floor levels. It can be seen that the CGPI value mildly increases with building height at a diminishing rate. In one specific case the CGPI has a value of 10.38 for a 20-storey building. It increases by 50% when the building height is doubled (i.e. 40-storey), and by 87% when the building height is tripled (i.e. 60-storey).

![Fig. 3: Variation of CGPI with overall building height](image)

3.2 Re-entrant Shape

The widespread development of residential buildings in Hong Kong based on a “cruciform” plan for individual tower is essentially a product of Building (Planning) Regulations [10]. Public space including lift lobbies and corridors is usually squeezed to a minimum at the building core. With its four wings radiating out from the core, typically a residential tower consists of eight apartments on a single floor, with two at each wing. A deep narrow “I-shape” re-entrant exists at each wing between the neighbouring flats. On some occasions, innovative architects go for sustainable design. Instead of the conventional cruciform plans, linear plan forms are sometimes adopted to enhance natural ventilation for not only apartments but also lobbies and corridors. Other re-entrant shapes thus evolve such as “T” and “L”. Fig. 4 shows the plan view of condensing units in a T-shape re-entrant. Also shown are the boundary lines of the CFD flow domain and the boundary conditions used in the simulation. The simulation results show that with the similar condenser layouts, the CGPI values of the air-conditioner operation in these re-entrant shapes are unlikely higher than the conventional I-shape [11].

3.3 Refuge Floor Location

Large openings at the enclosing walls of a re-entrant can be found on the refuge floor. The openings provide additional incoming flow paths for the ventilating air, other than those from the front end of the re-entrant. Fig. 5 compares the rising pattern of condenser on-coil temperature with floor level, at a 40-storey residential tower, for two different positions of the refuge floor, which are on 15/F (Position 1) and 25/F (Position 2).
respectively. The results were based on the same condenser arrangement scheme. It can be seen that the ingress of outside air at a refuge floor slightly reduces the on-coil temperature at several floor levels immediately above it, but it does not affect the overall temperature rise pattern. This indicates that there is a corresponding reduction of airflow at the front end, so that the overall air exchange rate remains the same even when there are additional openings. Hence the positions of the refuge floors are not critical, as far as overall energy performance is concerned. The corresponding values of CGPI for the two cases were found to be 15.51 and 15.57, which are almost identical.

![Plan view showing outdoor units in a T-shape re-entrant](image)

**Fig. 4:** Plan view showing outdoor units in a T-shape re-entrant

![Variation of condenser on-coil temperature with floor level for two different positions of refuge floor](image)

**Fig. 5:** Variation of condenser on-coil temperature with floor level for two different positions of refuge floor
3.4 Opening at Transfer Plate

A common structural design practice in Hong Kong is to have the structure of a residential tower resting on a transfer plate at the podium level. The transfer plate then forms the re-entrant bottom surface. In principle, the provision of an opening at the transfer plate immediately below the stack of condensing units at a re-entrant (see Fig. 6) could help bringing in additional ventilating air to lower down the on-coil temperature. However, the simulation results indicate that although the addition of this opening could improve the condenser working temperature at the first few floor levels, it does not have an effect on the working conditions at the upper floor levels [8]. The phenomenon is similar to the provision of refuge floor openings discussed above. Hence there is little justification for adding this bottom opening, especially when the building is tall.

However, the provision of bottom opening is useful in the case of a light well (or semi light well), i.e. when the ventilating air cannot flow in at the side of the building. Fig. 7 shows a photo taken from the podium of one re-entrant – the wall at the centre of the photo is the external facade of an adjoining building. This wall turns the lower 13 levels of the re-entrant into an enclosed “light well” and blocks the incoming airflow. In this case, the majority of the ventilating air for the lower levels can be from the bottom opening.

Fig. 7: External facade of the adjoining building viewed from the podium of the affected re-entrant

Fig. 6: Floor plan around a re-entrant with a bottom opening shown
4. RANDOMNESS IN EQUIPMENT OPERATION

It should be noted that CGPI as defined is useful to compare different building and equipment design schemes. It is not intended for predicting the annual electricity consumption of air-conditioning equipment in practice. The prediction of building energy consumption actually requires a different approach in thermal simulation [12,13]. In CGPI, the use of a diversity factor to reduce the overall heat dissipation rate is often a necessity. This in order to come up with reasonable on-coil temperature values for analysis. Otherwise the highest on-coil temperature reached in the simulation may fall outside the normal working range (i.e. maximum $T_o > 45^\circ C$). In so doing, the assumption that the correlation between the on-coil temperature and the COP of the air-conditioning unit remains the same as long as the room temperature remains stable and the operating load is not far from the peak load. With the same room temperature and condenser on-coil temperature, the vapour compression cycle remains relatively the same under a range of operating loads of the air-conditioning unit. It is also known that the operation of the condenser fans does introduce horizontal air movement at a re-entrant and cause the local $T_o$ values at different outdoor units deviate from the average air temperature at the corresponding floor level. To give a better understanding of this localized effect, an investigation of the effect of 100% outdoor unit operation on CGPI was executed. This is described below.

The impact of random equipment operation on $T_{om}$ had been evaluated making use of a hypothetical case: a 20-story building with the provision of 6 numbers of identical condensing units per floor level. These are at positions A to F in an I-shape re-entrant shown in Fig. 1. The total number of outdoor units in the re-entrant is therefore 120. Positions B and E are centred at 5m from the re-entrant front wall.

CFD simulations were carried out in 11 cases that are grouped into 3 categories (see Table 1). Category 1 is when all outdoor units are in operation and at 50% of the full capacity. Case Nos. 1 to 3 belong to this category with 3 different separation distances ($S$) between the neighbouring condensing units: 1.6 m, 0.8 m and 0.4 m respectively. In Category 2, all outdoor units at odd number floor levels are in operation and at full capacity; those at even number floor levels are in off-position. Examined under this category are Case Nos. 4 and 5 with $S$ equal to 1.6 m and 0.8 m respectively. Category 3 includes the 6 random cases, i.e. when only one half of the outdoor units are in operation but all are at full capacity. In each case, the on-off status of the individual condensers was assigned making use of a random number generator. Those 60 units with greater assigned numbers were taken as on and the rest 60 units were taken as off. In all 11 cases, the overall heat rejection rates by the 120 outdoor units are the same and at 270 kW. For illustration purpose, Table 2 lists the on-off status of the 120 condensers in Cases 6 and 7.

Fig. 8 shows graphically the results of Case 1 to Case 5. Because of the symmetry in physical arrangements and in heat dissipation, $T_{om}$ at positions A, B and C are almost identical to positions D, E and F at the same floor level. Fig. 9 shows the results in the random cases No. 6 to 11. The temperature patterns are found irregular, but in all cases the inner condensers (at positions C and F for instance) attained higher temperature levels.

<table>
<thead>
<tr>
<th>Category</th>
<th>Case No.</th>
<th>Condenser Operation</th>
<th>$S$ (m)</th>
<th>$T_{om}$ ($^\circ C$)</th>
<th>CGPI</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>All floors, 50% capacity</td>
<td>1.6</td>
<td>36.65</td>
<td>9.930</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>All floors, 50% capacity</td>
<td>0.8</td>
<td>36.41</td>
<td>9.283</td>
</tr>
<tr>
<td>1</td>
<td>3</td>
<td>All floors, 50% capacity</td>
<td>0.4</td>
<td>36.42</td>
<td>9.298</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>Alternate floors, 100% capacity</td>
<td>1.6</td>
<td>35.81</td>
<td>7.645</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>Alternate floors, 100% capacity</td>
<td>0.8</td>
<td>35.68</td>
<td>7.292</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>Random, 100% capacity</td>
<td>1.6</td>
<td>35.83</td>
<td>7.699</td>
</tr>
<tr>
<td>3</td>
<td>7</td>
<td>Random, 100% capacity</td>
<td>1.6</td>
<td>36.14</td>
<td>8.544</td>
</tr>
<tr>
<td>3</td>
<td>8</td>
<td>Random, 100% capacity</td>
<td>0.8</td>
<td>35.83</td>
<td>7.70</td>
</tr>
<tr>
<td>3</td>
<td>9</td>
<td>Random, 100% capacity</td>
<td>0.8</td>
<td>36.17</td>
<td>8.62</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>Random, 100% capacity</td>
<td>0.4</td>
<td>36.14</td>
<td>8.537</td>
</tr>
<tr>
<td>3</td>
<td>11</td>
<td>Random, 100% capacity</td>
<td>0.4</td>
<td>36.17</td>
<td>8.622</td>
</tr>
</tbody>
</table>
Table 1 lists the calculated results of $T_{\text{on}}$ and the corresponding CGPI values of the 11 cases. It can be seen that the air-conditioner performance is the worst in Category 1, i.e. when all outdoor units are in operation. Category 2 (alternate floor in operation) gives the best results and Category 3 (the random cases) falls between Categories 1 and 2. The results confirm that the randomness in equipment operation affects the overall energy performance even when the overall heat rejection rate remains unchanged. A simple reason for the worst performance in Category 1 is that the discharge air streams from all condensing units behave like air curtains to stop the outside air from reaching the inner part of the re-entrant. The starvation in ventilating air intensifies the air temperature rise. On the contrary in Category 2, the alternate floor operation provides more ample space for the inflow of outside air but less churning effect. So the results suggest that the CGPI, with the specific assumption of all outdoor units in operation, can give a benchmark value to compare the potential weakness in different building and equipment layout schemes.

![Condenser on-coil temperature (°C) vs floor level for Cases 1 to 5](image)

Fig. 8: Condenser on-coil temperature (°C) vs floor level for Cases 1 to 5
Fig. 9: Condenser on-coil temperature (°C) vs floor level for Cases 6 to 11
Table 2: Status of condensers at positions A to F in Case 6 and Case 7

<table>
<thead>
<tr>
<th>Floor Level</th>
<th>Case 6</th>
<th>Case 7</th>
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<tbody>
<tr>
<td></td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>20</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>19</td>
<td>0</td>
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<td>17</td>
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<td>16</td>
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<tr>
<td>15</td>
<td>0</td>
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<td>14</td>
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<td>1</td>
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<tr>
<td>12</td>
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<td>1</td>
</tr>
<tr>
<td>11</td>
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<td>1</td>
</tr>
<tr>
<td>10</td>
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<td>1</td>
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<td>2</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

(‘1’ indicates ON and ‘0’ indicates OFF)

5. CONCLUSION

In real buildings, the thermal environment of a building re-entrant as a result of the heat dissipation from the outdoor condensing units varies all the time. The complexity is owing to the continuously changing equipment operation and climatic condition. These add difficulties to the design work of the professional engineers. The CGPI approach is able to simplify the thermal analysis by using a steady state fluid flow and thermal model, and allows the use of a single parameter to evaluate different building design and equipment layout schemes.

Based on realistic building and equipment operation data, various comparative studies concerning building geometry had been performed. The findings are summarized in this paper. It was found that the CGPI value increases with the overall height of a building at diminishing rate. The openings at the refuge floor or on the transfer plate are not effective to improve the air exchange condition; they only help to lower down the on-coil temperature locally, without changing the overall temperature distribution. Re-entrant shapes adopted in innovative sustainability design like “T” and “L” normally will not intensify the heat accumulation than the traditional simple I-shape.

An examination of the effect of random equipment operation on the overall energy performance of the split-type air-conditioners had been executed. In the 11 cases of hypothetical study grouped under 3 categories and with 3 different condenser separations, it was found that those cases with all condensing units in operation give the worst overall energy performance. As 100% condenser operation is a basic assumption in the CGPI approach, hence CGPI is verified to be a useful design evaluation parameter that can benchmark an unfavourable working condition.

ACKNOWLEDGEMENT

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REFERENCES

2. M. Bojic, M. Lee and F. Yik, “Flow and temperature outside a high-rise residential building


