

Thermal plume simulation of VRF air conditioners for cooling system in high-rise buildings: A case study in China

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ABSTRACT

Variable refrigerant flow (VRF) air conditioning system is widely used in commercial and residential buildings for space cooling and heating. However, some practical VRF systems used in high-rise buildings cannot work efficiently or even stop working because of the relatively high ambient temperature, caused by thermal plume effect of exhaust heat from outdoor units. In this paper, the thermal plume air flow of layer-based VRF systems is investigated through computational fluids dynamics (CFD) simulation. Moreover, an illustrative example in a 30-storey office building in China is conducted to optimize the layout of VRF outdoor units. Preliminary results show that the exhaust heat of outdoor units can cause ascending thermal plume flow, leading to higher inlet temperatures for VRF air conditioners on upper floors. It also indicates that enlarging the distance between outdoor units on different floors is an effective way to impair such thermal plume effect and improve the system thermal performance. For the studied case, a modified layout of VRF outdoor units is presented with floor interval, and the average inlet temperatures can be decreased by 22%. This work can provide guidance to the optimization layout design of practical VRF air conditioning systems used in high-rise buildings.

Key words: air conditioner; outdoor air; inlet temperature; thermal plume; simulation.

INTRODUCTION

With the rapid industrialization and modernization over the two recent decades, the global total energy consumption has grown by 49% (International Energy Agency, 2006). Therein, buildings account for more than 30% of the total energy consumption and the percentage keeps increasing, owing to the rapid urbanization (Luis et al., 2008, & Shwehdi et al., 2015). During the same period, building energy consumption in China has increased with an average annual rate of over 10% (Zhang et al., 2016). According to the latest statistics analysis, heating ventilation and air conditioning (HVAC) system accounts for about 70% of total building energy consumption in China (Zhang et al., 2016, & Ozbek, 2016). Hence, improving the energy efficiency of HVAC systems is of high significance in building energy saving (Hasan et al., 2009).

Variable refrigerant flow (VRF) is an advanced air conditioning technology, which uses refrigerant as the cooling and heating medium directly. The refrigerant is conditioned by a single outdoor condensing unit and is then circulated within the building to multiple indoor terminal devices, such as fan coils (Yun et al., 2016). Compared to traditional air conditioners, VRF systems show many obvious advantages, including great energy and cost saving potential, low greenhouse gas emissions, high operation reliability, and flexibility (Aynur et al., 2008). During recent years, VRF systems are widely used in midsize office buildings and large commercial buildings, accounting for more than 24%

of global commercial air conditioning market (Aynur et al., 2008). Many researchers are dedicated to the thermal performance analysis and improvement of VRF air conditioning systems. Liu et al. (2004) studied the variable speed compressors and the expansion valves installed in individual indoor units responding to changes in the zone's space cooling or heating loads. Tu et al. (2011) applied the VRF system to individualized comfort control by controlling the amount of refrigerant flow to each indoor unit. Yun et al. (2016) further stated that VRF systems can be also utilized on some special occasions where simultaneous heating and cooling operations are required.

However, in real engineering applications, the thermal performance of practical VRF air conditioning system highly depends on the working conditions since it often operates under various complex environments. Lin et al. (2015) maintained that the ambient temperature had a great influence on the coefficient of performance (COP) of VRF systems; in terms of that higher ambient temperature leads to higher condensing temperature for outdoor units, decreasing COP accordingly. Moreover, Gao et al. (2008) found that such influence became more obvious in high-rise buildings since layer-based VRF air conditioners were often installed at the same location on different floors so that the exhaust heat from the lower systems might impact the outdoor air temperature for the upper systems. Li et al. (2009 & 2010) conducted experiment on the inlet temperature control for VRF systems and took different actions to enhance the heat transfer for air-cooled outdoor condensing unit.

Therefore, effective measures should be taken to improve the working conditions for VRF outdoor units, especially in high-rise buildings. Before that, to investigate the outdoor air flow state and temperature distribution is of high necessity to understand the effect mechanism of thermal plume flow caused by the exhaust heat from VRF outdoor units (Chaoyu et al., 2009). Nevertheless, the analytical solution of the outdoor air flow state near VRF air conditioners is hard to obtain, as a result of the system complexity in practical engineering fields (Zhang et al., 2016). Instead, computational fluid dynamics (CFD) can solve such simulation problems involving fluid flows through numerical analysis and algorithms (Karmare et al., 2010). And CFD method has been widely used in various energy system simulation and analysis, such as solar energy system (Gan et al., 2009), indoor air quality control (Zhai et al, 2014), heat exchange and heat pump (Zsebek & Sitkujr, 2001), and HVAC systems (Zhang et al., 2016).

In this paper, the thermal plume air flow of the layer-based VRF systems is investigated through computational fluids dynamics (CFD) simulation. Moreover, an illustrative example of practical VRF system in a 30-storey office building in Shenzhen is conducted and two different layouts of layer-based VRF outdoor units are presented. Then the inlet temperature distributions are analyzed and compared to show the thermal plume effect caused by the exhaust heat. This work can offer guidance to the optimization layout design of practical VRF air conditioning systems used in high-rise buildings.

MATHEMATICAL MODEL

For the incompressible fluid, partial differential equations can be obtained from Navier–Stokes equation. While the air flow of VRF outdoor units often lies in turbulent one (Yamada, 1982). The numerical solution of the Navier–Stokes equations for turbulent flow is extremely difficult, and due to the significantly different mixing-length scales that are involved in turbulent flow, the stable solution of this requires such a fine mesh resolution that the computational time becomes significantly infeasible for calculation or direct numerical simulation. To address this problem, time-averaged equations such as the Reynolds-averaged Navier–Stokes equations (RANS), supplemented with turbulence models, are used in practical computational fluid dynamics (CFD) applications (Walters & Cokljat, 2008). In this paper, the k – ϵ model is utilized to bring closure to the RANS equations.

Regardless of the flow assumptions, a statement of the conservation of mass is generally necessary. It can be achieved through the mass continuity equation:

$$\frac{d\rho}{dt} + \nabla \cdot (\rho V) = 0 \quad (1)$$

where ρ and V represent the flow density (kg/m^3) and velocity vector (m/s), respectively. Since there is no change in density over time, there is

$$\nabla \cdot (\rho V) = \sum_i \frac{\partial(\rho V_i)}{\partial x_i} = -\frac{d\rho}{dt} = 0 \quad (2)$$

Then according to Newton's second law of motion, the accelerated velocity of the air flow is a function of both surface and mass force:

$$\frac{d(\rho V)}{dt} = F + \nabla \cdot P \quad (3)$$

where F and P represent body force and mass force, respectively. Based on the generalized Newtonian viscous stress, the momentum equation is

$$\frac{\partial(\rho V)}{\partial t} + V_j \frac{\partial(\rho V_i)}{\partial x_j} = F - \frac{\partial P}{\partial x_i} + \mu \nabla^2 V \quad (4)$$

where μ is the kinematic viscosity (kg/m²s) and P is the static pressure (Pa). Then the energy balance equation is as follows:

$$\frac{\partial \rho H}{\partial t} + \frac{\partial}{\partial x_i} (V_i \rho H) = \frac{\partial}{\partial x_j} \left(\frac{\lambda}{c_p} \frac{\partial H}{\partial x_j} \right) + S \quad (5)$$

where H , λ and c_p mean the enthalpy (kJ/kg), thermal conductivity (W/mK), and specific heat (kJ/kgK), respectively, and S represents the heat source (kW). Reynolds-averaged Navier–Stokes (RANS) simulations use the Boussinesq eddy viscosity hypothesis to calculate the Reynolds stresses (Zhao et al., 2003); the turbulent equation using k - ε model is expressed by

$$\rho \frac{\partial K}{\partial t} + \rho V_i \frac{\partial K}{\partial x_i} = \frac{\partial}{\partial x_i} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial K}{\partial x_i} \right] + \mu_t \frac{\partial V_i}{\partial x_j} \nabla \cdot V - C_a \rho \frac{k^3}{l} \quad (6)$$

where C_a is a constant; μ_t and σ_k represent the kinematic viscosity for turbulent flow and Prandtl number of turbulence kinetic energy, respectively. For the energy dissipation in such turbulent air flow, there is

$$\rho \frac{\partial \varepsilon}{\partial t} = \frac{\partial}{\partial x_i} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial \varepsilon}{\partial x_i} \right] + C_b \frac{\varepsilon}{K} (G_k + C_c) - C_d \rho \frac{\varepsilon^2}{K} \quad (7)$$

where C_b , C_c , C_d are all empirical constants. In the finite volume method, the governing partial differential equations (typically the Navier-Stokes equations, the mass and energy conservation equations, and the turbulence equations) are recast in a conservative form and then solved over discrete control volumes (Shu, 2003). This discretization guarantees the conservation of fluxes through a particular control volume. The finite volume equation yields governing equations in the form. Moreover, the semi-implicit method for pressure linked equations-consistent (SIMPLEC) algorithm can be used to modify the velocity vector (Johansson & Davidson, 1995). In the following section, a layer-based VRF air conditioning system in a high-rise office building is taken as the illustrative example to investigate the outdoor air temperature distribution caused by the exhaust heat from the VRF outdoor units through air flow simulation.

CASE BUILDING IN CHINA

A south-facing 30-storey office building is located at Shenzhen (Southern city in China). According to the building thermal design standard in China and local climate conditions, Shenzhen belongs to Hot Summer & Warm Winter climate zone (Zhang et al., 2013). Furthermore, the daily average temperature in Shenzhen can reach as high as 31 °C in summer, so that cooling demand constitutes the dominant load for such a high-rise office building. Figure 1 gives

the layout of the standard floor (800 m²). For such a high-rise building, the layer-based VRF air conditioning systems are designed for space cooling in summer; in terms of that VRF air conditioners are installed independently on each floor and the outdoor units are all set in the equipment rooms, respectively.

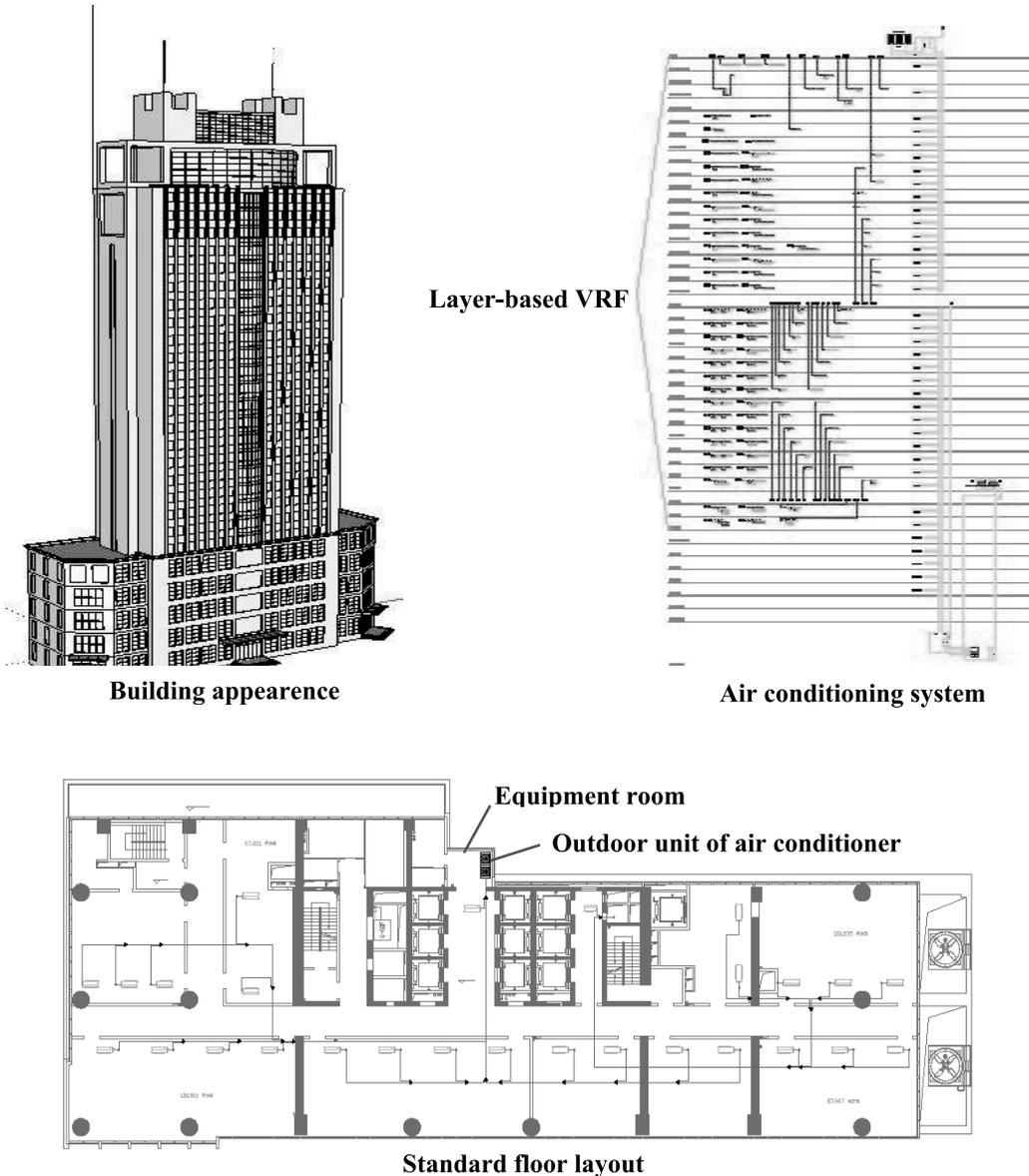


Fig. 1. A 30-storey office building in Shenzhen, China, and the designed VRF air conditioning system.

For installed capacity determination of VRF air conditioner, the cooling load for this office building standard floor is estimated to be 64 kW in a typical summer day. The design parameters of the chosen VRF air conditioner are listed in Table 1. It can be seen that the cooling capacity is 69 kW, with coefficient of performance (COP) arriving at 3.79 under the rated working condition. Thus the rated exhausted heat for the outdoor unit reaches 87.2 kW, with 7.2 kg/s air flow rate.

Table 1. Design parameters of the multi-couple air conditioner.

Item	Unit	Value
Name		Multi V III
Type		ARU0693WT4
Electrical source	$\phi/V/Hz$	3/380/5
Cooling power	kW	69
Coefficient of performance (COP)		3.79
Size (W×H×D)	mm	760×1680×1840
Weight	kg	480
Air flow rate	kg/s	7.2
Refrigerant		R410a (12.8 kg)
Connected fluid pipe	mm	15.88
Maximal indoor air handling units		39
warning upper inlet air temperature	°C	43

The inlet air temperature of the outdoor unit has a substantial impact on the thermal performance of the multi-couple air conditioner, in terms of COP decreases with increasing inlet air temperature. What is worse, if the inlet temperature arrives at the warning upper threshold value (i.e., 43 °C in this case), the air conditioner will shut down automatically. Therefore, heat exhaust enhancement for the outdoor units is of high significance in maintaining the stable working conditions for the whole system, so that the arced exhaust hoods are utilized to guarantee the emission of exhausted heat (Figure 2).

**Fig. 2.** Outdoor units of VRF air conditioner with arced exhaust hood.

However, due to the same location of outdoor units on each floor, the high temperature exhaust heat can cause thermal plume effect outdoor. Thus the gradually ascending heat will inevitably increase the outdoor air temperature for upper layers, leading to bad working conditions for the outdoor units on those floors. Hence, it is necessary to analyze the feasibility of layer-based VRF air conditioning system in such a high-rise building, based on the thermal plume simulation of the outdoor units.

CFD SIMULATION

To address such an air flow simulation problem, the off-shelf software, Fluent Airpak, can be used. As Figure 3 shows, the outdoor zone near the equipment room is regarded as the target simulation domain ($10 \times 10 \times 100 \text{ m}^3$). According to the design parameters, it is designated that exhaust heat is 87.2 kW and air flow rate 7.2 kg/s for the

outdoor units. Besides, it is assumed that ambient temperature is 35 °C in Shenzhen and air conditioning system works at full load. Table 2 gives the results of the mesh independence study, where two meshing arrangements are compared. It can be seen that the average relative error for meshing in $0.5 \times 0.5 \times 5$ is lower than 0.7 %, which is quite acceptable for engineering applications.

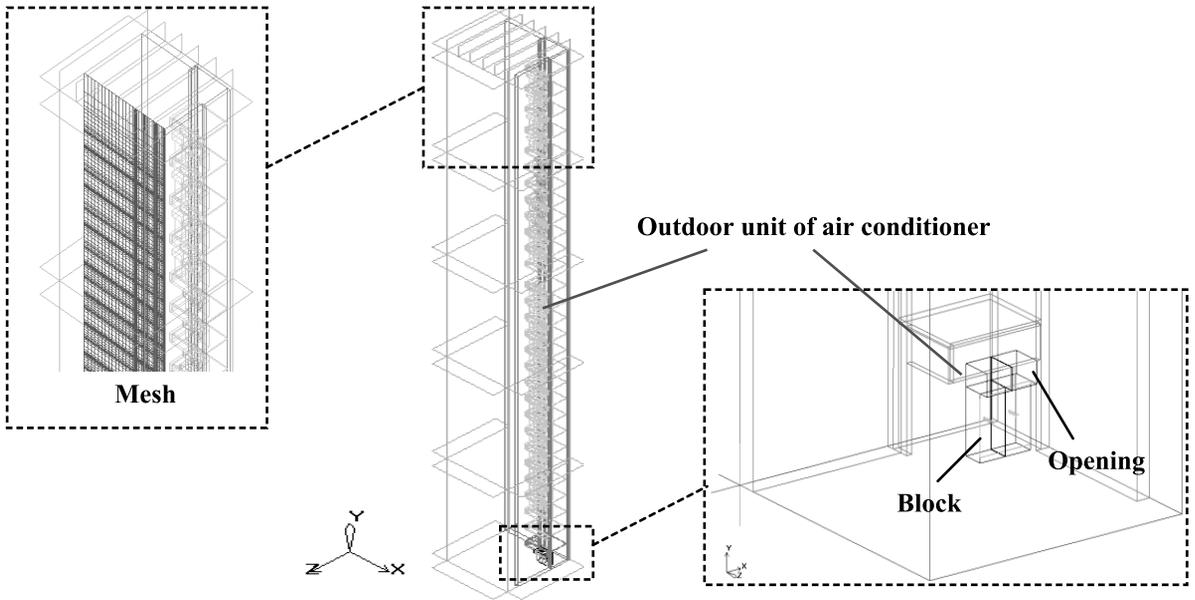


Fig. 3. CFD simulation model of outdoor units of VRF air conditioner in Airpak.

Table 2. Mesh independence study for simulation.

Floor	Outdoor temperature (°C)		Relative error (%)
	Grid $0.5 \times 0.5 \times 5$	Grid $0.4 \times 0.4 \times 4$	
1	33.0558	33.302	0.74
2	34.4518	34.4744	0.07
3	35.2829	35.3389	0.16
4	36.8479	36.9015	0.15
5	35.1007	35.4161	0.90
6	39.2216	39.5977	0.96
7	40.6106	40.9503	0.84
8	41.6411	41.9470	0.73
9	42.6715	42.9216	0.59
10	43.6319	43.8354	0.47
11	44.5343	44.7264	0.43

12	45.3927	45.6152	0.49
13	46.2125	46.5016	0.63
14	46.9996	47.3327	0.71
15	47.7540	48.1780	0.89
16	48.4804	48.8702	0.80
17	49.2205	49.6061	0.78
18	50.3862	50.6744	0.57
19	45.0083	45.2334	0.50
20	49.8062	50.1451	0.68
21	50.4852	50.7392	0.50
22	51.5000	51.6145	0.22
23	52.1534	52.2038	0.10
24	52.1579	52.4928	0.64
25	52.1966	52.6684	0.90
26	52.5704	52.7135	0.27
27	52.8464	52.9289	0.16
28	53.0040	53.4065	0.76
29	53.3681	53.7813	0.77
30	53.8402	53.9273	0.16

Based on the established mathematical and simulation models, through finite volume method, the aforementioned governing partial differential equations (Navier-Stokes equations, energy conservation equation, and the turbulence equation) are recast in a conservative form and then solved over discrete control volumes. The following section gives the simulation results.

RESULTS AND DISCUSSION

Figure 4 shows the air temperature variations of the outdoor units of the VRF air conditioners for different layers. Due to the thermal plume effect of high temperature exhaust heat, the inlet and outlet temperatures increase gradually from the bottom to the top of this high-rise building. So the working conditions of the outdoor units become worse with the increasing floor height, which brings undesirable influences on the thermal performance of the air conditioning system. It can be seen that the inlet temperature can reach more than 50 °C for the upper layers, higher than the warning upper threshold value. As a consequence, the equipment has to stop working. So the initial design and layout of the layer-based VRF air conditioning system is completely inapplicable for the high rise building.

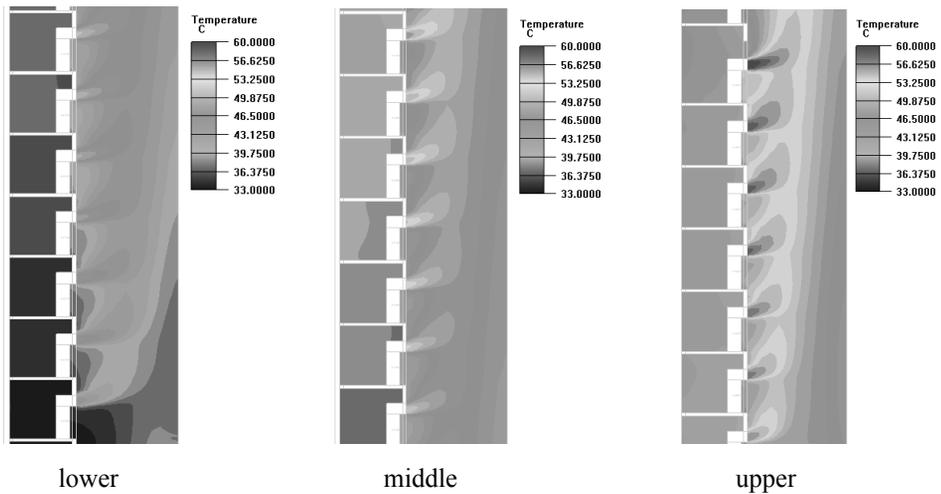
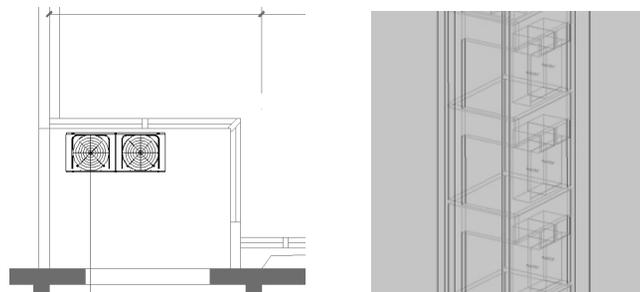
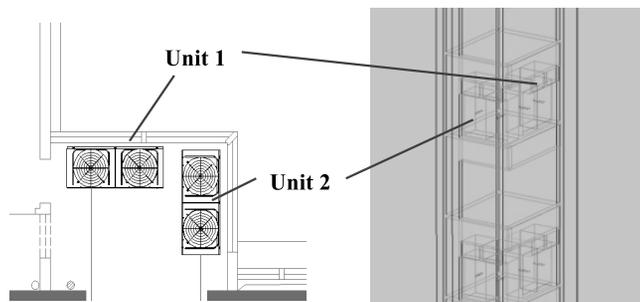


Fig. 4. Outdoor air temperatures on different floors for VRF air conditioner.

Based on the aforementioned analysis, the key to address such a problem is to avoid the short-cut of air flow between neighbouring layers derived from the thermal plume effect. One effect way is to deliberately enlarge the interval space between outdoor units on different layers. So the alternative layout of the VRF air conditioning system is shown in Figure 5(b).



(a) Original layer-based layout



(b) Modified layer-based layout with floor interval

Fig. 5. Alternatives of VRF air conditioning system in the high-rise building.

In the modified case, two outdoor units of the VRF air conditioner working for two different floors are set in one equipment room with different directions. So the distance between neighbouring layer systems is increased, to reduce the influence of the thermal plume caused by the exhaust heat. Through the same simulation method, the temperature variations for the modified case can be obtained (Figure 6).

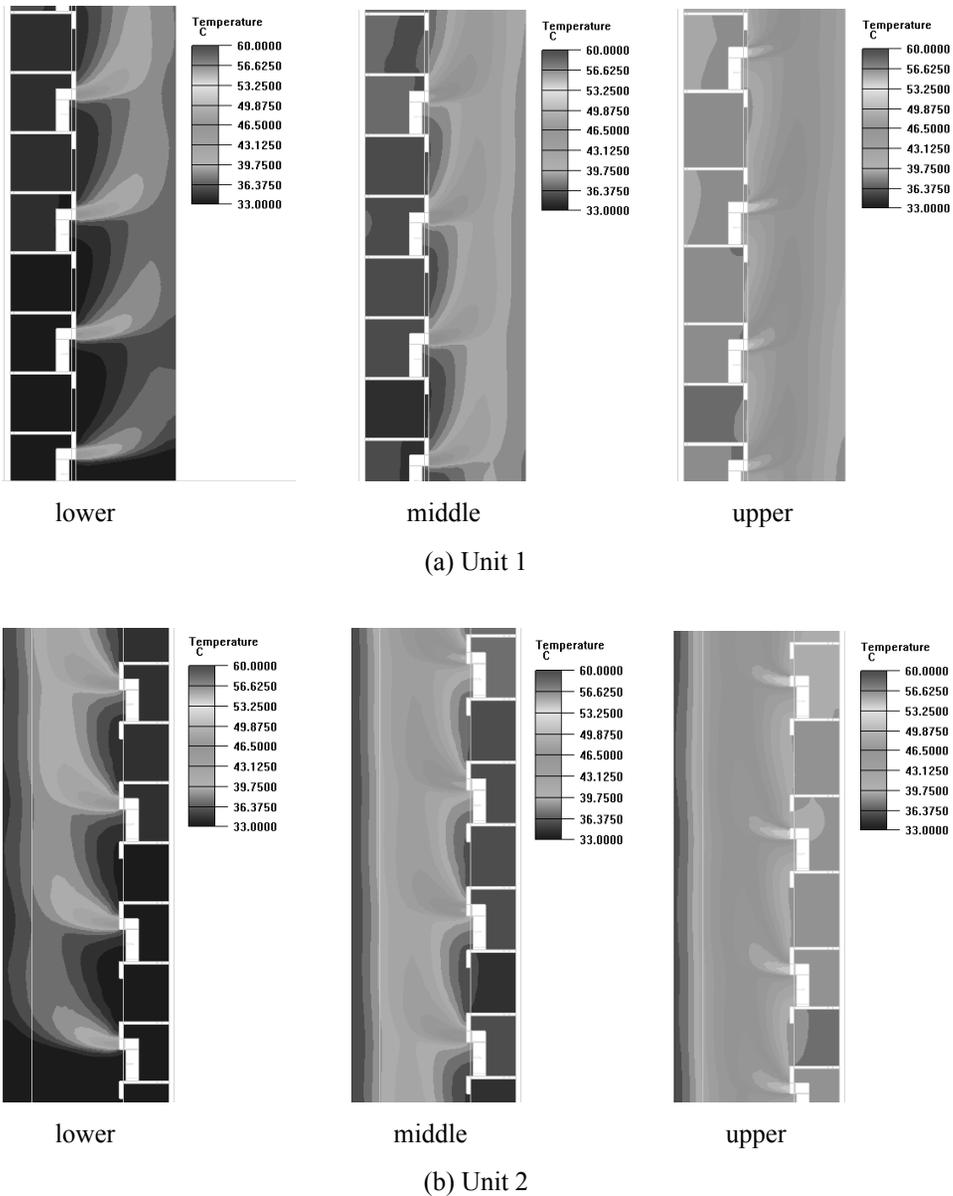


Fig. 6. Outdoor air temperatures on different floors for VRF air conditioner with floor interval.

It is clear that, with floor interval, the working conditions for the outdoor units are highly improved, with much lower inlet and outlet temperatures compared to the previous case. Even on the upper floors, the highest inlet temperature just stands at 40 °C, within the warning temperature threshold. Figure 7 and Figure 8 give the horizontal temperature distributions of the outdoor units on the 3rd floor and the 29th floor, respectively.

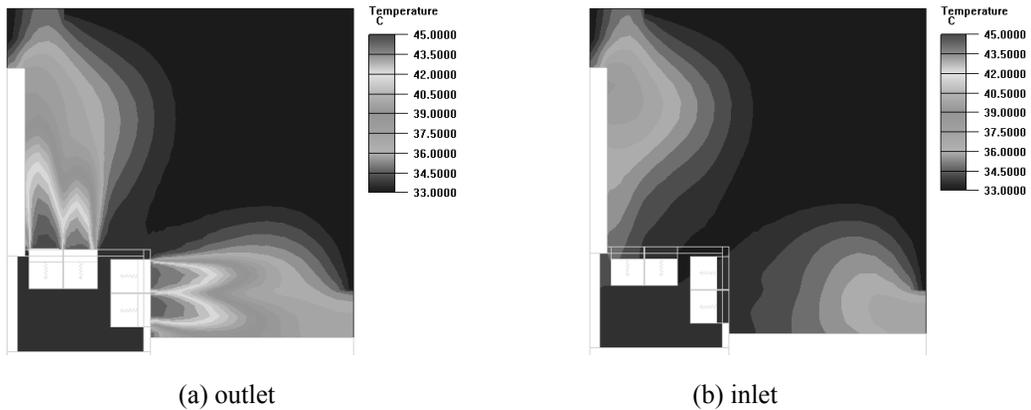


Fig. 7. Horizontal temperature distribution of VRF outdoor units on the 3rd floor.

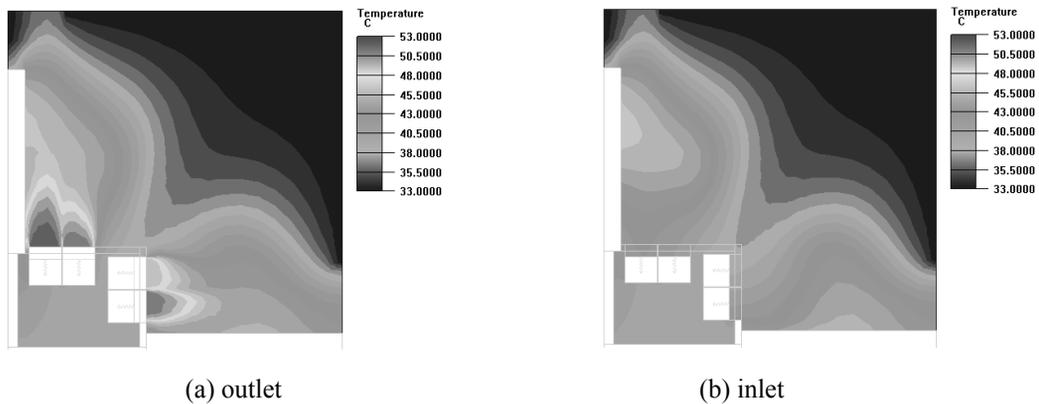


Fig. 8. Horizontal temperature distribution of VRF outdoor units on the 29th floor.

The average outside air temperature of the upper floor is about 8°C higher than that of the lower floors, due to the ascending thermal plume flow. The results also indicate that, even for the same outdoor unit equipment, there still exists a temperature difference between the two subsystems. The one closer to the building external wall is of higher inlet temperature than another, due to the thermal plume flow obstruction of the building envelopes. So the building exterior structures also have great impacts on determining the layout of VRF air conditioning systems for high-rise buildings. Figure 9 gives the comparison on the average inlet temperature of the VRF air conditioner between these two cases under the same given conditions. For case 1, where outdoor units are set on each floor, all the VRF air conditioners on 10th and higher floors cannot work completely, because of the high inlet temperature caused by thermal plume. However, for case 2 with enlarged distance between neighbouring systems, all air conditioners can work steadily in such a high-rise office building.

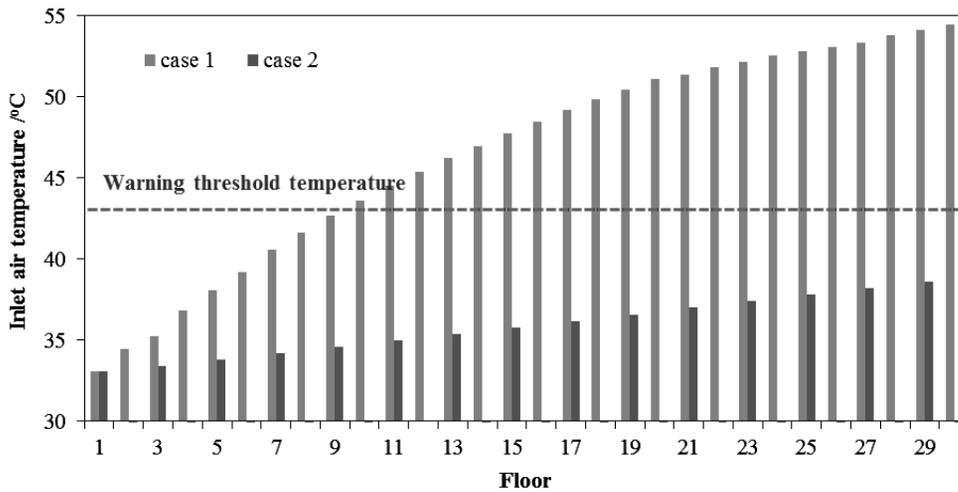


Fig. 9. Inlet temperature comparison of VRF air conditioning systems on different layers between two cases.

CONCLUSION

VRF air conditioning system is of high energy efficiency, low operation cost, high flexibility, and reliability. The thermal performance of VRF system highly depends on the ambient air temperature of outdoor units. In this paper, the thermal plume air flow of the layer-based VRF systems is investigated through CFD simulation. Moreover, an illustrative example of practical VRF system in a high-rise office building in Shenzhen is conducted and analyzed to optimize the layout of the outdoor units. Preliminary results show that:

- (1) The exhaust heat of outdoor units can cause ascending thermal plume flow, leading to higher inlet temperatures for the upper VRF air conditioners in high-rise buildings.
- (2) The inlet temperature increases with increasing floor height and it can arrive at 50 °C at the 30th floor for the studied case so that the VRF air conditioners cannot work for the upper layers because the inlet temperatures exceed the warning upper threshold value (43 °C).
- (3) Enlarging the distance between outdoor units on different floors is an effective way to improve the working conditions for VRF systems in high-rise buildings.
- (4) For the illustrative example with floor interval, the average inlet temperatures can be decreased substantially by 22%. Even on the upper floors, the highest inlet temperature just stands at 38 °C, within the warning temperature threshold. Thus all the VRF air conditioners can work steadily and efficiently.

Accordingly, the layout of VRF air conditioners plays an important role in the thermal performance of the whole system in high-rise buildings, considering the thermal plume effect caused by the exhaust heat from outdoor units. The present work only discusses a simple case to show the preliminary application of air flow simulation in optimizing the design of layer-based VRF air conditioning systems. In practical engineering fields, the optimal layout for different kinds of systems highly depends on various factors, such as building types, user load characteristics, chosen air conditioners, and economic considerations. Although the specific results obtained for the studied case may not be applicable to all situations, the analysis method used here is general. This work can offer guidance to the optimization design of practical VRF air conditioning systems.

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APPENDIX

Nomenclature

c_p	specific heat (kJ/kgK)
C	constant
COP	coefficient of performance
CFD	computational fluids dynamics
F	mass force (N/ m ³)
H	enthalpy (kJ/kg)
HVAC	heating ventilation and air conditioning
l	effective length (m)
P	pressure (Pa)
S	heat source (kW)
t	time (s)
V	velocity (m ² /s)
VRF	variable refrigerant flow
ρ	density (kg/ m ³)
μ	kinematic viscosity (kg/ms)
λ	thermal conductivity (W/mK)

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محاكاة عمود سحب حراري في مكيفات الهواء VRF لأنظمة التبريد في المباني الشاهقة: دراسة حالة في الصين

*ين تشانغ، **شياو تشانغ، *شوروي غو و*انشن لونج
*كلية الهندسة المعمارية والبيئة، جامعة سيتشوان، تشنغدو، الصين
**شركة هاواي للتكنولوجيا المحدودة، شنتشن، الصين

الخلاصة

أنظمة تكييف الهواء التي تعمل بنظام التدفق المتغير لسائل التبريد (VRF) تُستخدم على نطاق واسع في المباني التجارية والسكنية لتبريد وتدفئة الأماكن. ومع ذلك، فإن بعض أنظمة VRF المستخدمة في المباني الشاهقة لا تعمل بكفاءة أو قد تتعطل بسبب درجة الحرارة المحيطة المرتفعة نسبياً، والناجمة بسبب تأثير حرارة العادم على عمود السحب الحراري في الوحدات الخارجية. في هذا البحث، تم دراسة تدفق الهواء بالعمود الحراري لأنظمة VRF المرتكزة على الطبقة من خلال المحاكاة الحاسوبية لديناميكيات الموائع (CFD). علاوة على ذلك، تم تنفيذ مثال توضيحي في مبنى مكاتب مكون من 30 طابق في الصين لتحسين تصميم وحدات VRF الخارجية. وأشارت النتائج الأولية أن حرارة العادم في الوحدات الخارجية يمكن أن تسبب تدفق حراري متصاعد في العمود، مما يؤدي إلى ارتفاع درجات الحرارة في مدخل مكيفات الهواء VRF في الطوابق العليا. وتشير كذلك إلى أن توسيع المسافة بين الوحدات الخارجية في الطوابق المختلفة هو وسيلة فعالة لإضعاف مثل هذا التأثير الحراري للسحب وتحسين الأداء الحراري للنظام. وبالنسبة للحالة التي تمت دراستها، تم تقديم تصميم مُعدّل لوحدات VRF الخارجية مع فاصل أرضي ويمكن تخفيض متوسط درجات حرارة المدخل بنسبة 22%. ويمكن أن يصبح هذا العمل دليلاً لتصميم النموذج الأمثل لأنظمة تكييف الهواء VRF العملية والمستخدمة في المباني الشاهقة.