HVAC SYSTEM CONFIGURATIONS, AN ENERGY ASPECT

Y Zhang[1,*], J A Wright[2] and V I Hanby[1]

[1] Institute of Energy and Sustainable Development, De Montfort University,
Leicester, LE1 9BH, UK
[2] Department of Civil and Building Engineering, Loughborough University, Loughborough,
Leicestershire, LE11 3TU, UK

ABSTRACT

This paper studies energy implications of HVAC system configuration by analysing energy balance and psychrometrics of typical systems. Three criteria have been established: (1) the ability to minimize outside air load; (2) the ability to eliminate simultaneous cooling and heating, and use mixing effectively; and (3) the availability of inter-zonal airflow. Configurations that meet these criteria would be able to deliver desired indoor air quality with reduced energy consumption. A number of 2-zone configurations, including single-duct, dual-duct, and fan-coil-based variations, and a conceptual optimal configuration, have been tested on an example building. The results of this study are applicable to more complex systems.

INDEX TERMS

HVAC, Configuration, Energy efficiency, Optimization, IAQ

INTRODUCTION

In the early stage of HVAC system design, the choice of configuration is one of the decisions that significantly affects the performance of the final system, involving design options such as zone setting, choice of equipment, arrangement of air circulation and operation strategy. A "good" configuration enables the system to provide a high quality indoor environment, with minimum cost and environmental impact. ASHRAE (2000) provides a list of typical HVAC systems, including single-zone and multi-zone systems; single-duct, dual-duct, and multi-deck systems; constant air volume (CAV) and variable air volume (VAV) systems; and packaged systems, such as fan-coil units and unitary systems. The performance of these systems, including energy efficiency and indoor air quality (IAQ) impacts, has been extensively studied. Novel HVAC system schemes have also been developed to deliver better IAQ with less thermal energy consumption (Cui et al. 2003, Song and Liu, 2004).

Although HVAC systems vary in schematic, operation strategy, working medium and packaging, it is possible to represent the configuration of these systems as a set of basic psychrometric processes connected by air flows (Zhang, 2005). This paper studies various aspects of HVAC system configurations, using psychrometric and energy balance analysis. A number of configurations are evaluated for an example 2-zone building. An "optimal" configuration is proposed for 2-zone systems, and its performance advantages are quantified by simulation.

HVAC SYSTEM CONFIGURATION

Figures 1 ~ 4 show the configurations of four HVAC systems. The configuration in figure 1 is a 2-zone single-duct VAV system (ASHRAE, 2000). The small circles and boxes in the figure

---

[*] Corresponding author email: yizhang@dmu.ac.uk

represent air mergers and splits, respectively. Outside air is mixed with the return air, and subsequently conditioned by the heating and cooling coils in the central plant, before being supplied to each zone. The zones are equipped with re-heating terminals, which also control humidity ratio of the supplied air. Figure 2 represents a 2-zone dual-duct VAV system (ASHRAE, 2000). Similarly, humidifiers are added to provide humidity control. The configurations in Figure 3 and 4 are based on fan-coil systems. Each zone is equipped with one fan-coil unit, comprising heating and cooling coils, and a humidifier. The two zones in Figure 3 are arranged sequentially, where relief air from one zone is directed to the other before exhausting to the ambient. In figure 4, the two zones are arranged in parallel as they both discharge to the ambient. In both fan-coil-based configurations, fresh air is supplied untreated, via dedicated ducts. In each diagram, there is also a recirculation path, whose function will be further discussed.

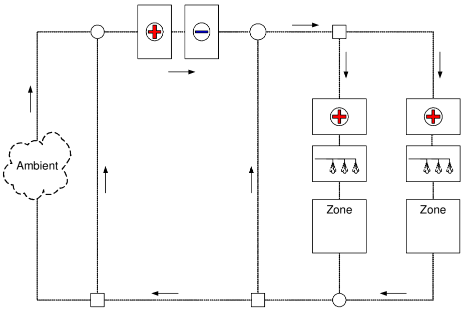

Figure 1. *Single-duct system*

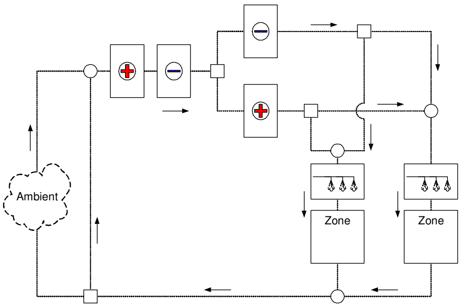

Figure 2. *Dual-duct system*

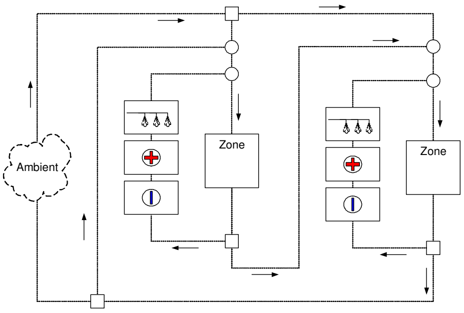

Figure 3. *Fan-coil and fresh air system – Sequential arrangement*

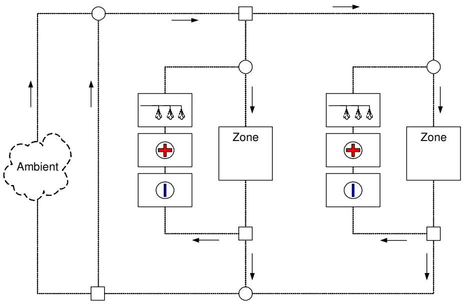

Figure 4. *Fan-coil and fresh air system – parallel arrangement*

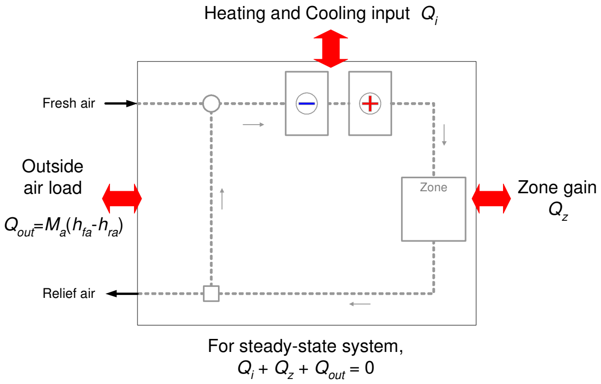

Figure 5. *Energy balance of HVAC system*

ENERGY ANALYSIS

The energy balance of a HVAC system is shown in Figure 5. Three groups of thermal energy flow are identified – the gain/loss in the zone(s); the active heating/cooling input(s), and the gain/loss due to air exchange with the ambient environment. The objective of energy-efficient

HVAC configuration design is to minimize the heating and cooling duties by reducing (1) outside air load; (2) zone load and (3) energy waste due to the air-conditioning process.

Outside air load

During temperate seasons, free cooling (when the enthalpy of outside air is lower than that inside) is an energy efficient way of removing excess heat from a building. In winter and summer however, fresh air is often a significant part of the system load. The fresh air load is calculated by the enthalpy difference between fresh air and zone air, multiplied by mass flow rate. Therefore, it can be minimized by either reducing outside air flow, reducing the enthalpy difference, or both. The minimum outside air flow required to maintain IAQ of the conditioned zones is usually the control target during summer/winter operations. For multi-zone systems, however, the minimum outside air flow is not achievable in some conditions. For example, the 2 zones in figure 6 have the same minimum outside air requirement (Moa_{min}), whereas their cooling loads are different (10kW vs. 5kW). Without a re-heating coil at the supply terminal to Zone1, the system satisfies the cooling demands in both zones by supplying Zone2 twice the air volume as that is supplied Zone1. Assuming that the minimum outside air volume (Moa_{min}) is supplied to Zone1, the volume of outside air that Zone2 receives is hence $2Moa_{min}$. In total, $3Moa_{min}$ is drawn from ambient, instead of $2Moa_{min}$, resulting in 50% higher outside air load. The dual-duct systems (Figure 2) have a similar problem, when the loads and outside air demands for each zone are out of proportion. This applies to all multi-zone systems where cooling/heating loads and outside air distribution are handled centrally. Separate zone load handlers, and dedicated fresh air circuits, are preferred to avoid this problem.

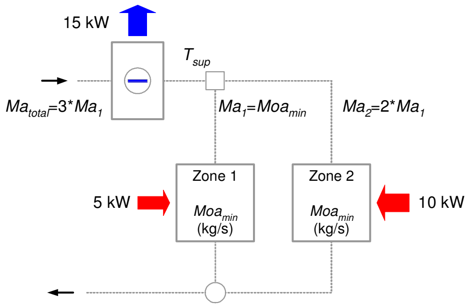

Figure 6. *Fresh air requirements vs. cooling demands*

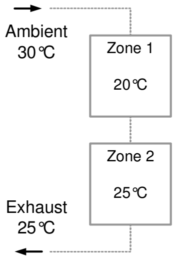

Figure 7. *Minimizing enthalpy difference between fresh and relief air*

The second approach to minimize fresh air load is to reduce the enthalpy difference between the fresh air and relieved air. Consider the two zones at different indoor conditions in Figure 7, exhausting warmer air from Zone 2 is preferred to exhausting from Zone 1.

Inter-Zone air flow and load offset

In some cases it is possible to reduce overall zone load by the use of inter-zonal air flow. Each zone served by a multi-zone HVAC system has the potential to act as a heat source or sink. Provided that at least two zones have opposite loads (heating vs. cooling), then the potential exists to offset the zone loads. This could be achieved by using a heat pump, or simply circulating air between zones, though restrictions apply in the later case. For example, the two zones in Figure 8 are maintained at 20°C and 25°C, respectively. The 5kW sensible gain to Zone 2 could be reduced by passing some air from the Zone 1 (20°C) to Zone 2 (25°). Meanwhile the 5kW heating load in Zone 1 can be offset by the air circulated from Zone 2 (Figure 8A). An economizer that re-circulates the return air has the similar effect (Figure 8B). Relief air from both zones are mixed and fed back to each zone. Since the returned air temperature is 22.5°C, the circulated air volume required to offset the load in each zone is doubled, implying higher fan energy cost. Figure 8C shows the condition that Zone 1, which has heating demand, is maintained at higher temperature then Zone 2. As passing the air from Zone 2 to Zone 1 would increase the gain to Zone 1, and vice versa, inter-zone circulation is not recommended.

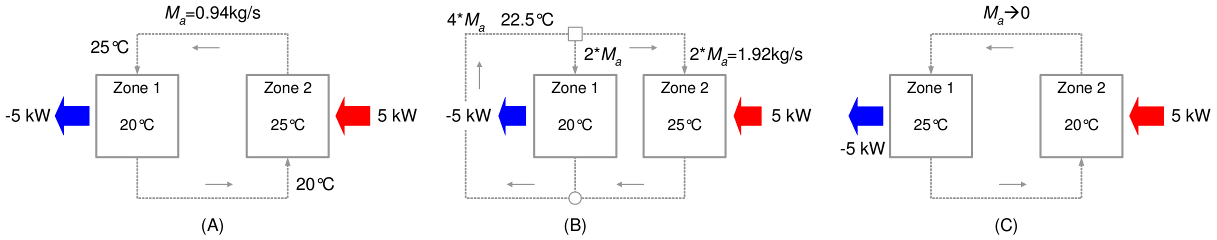

***Figure 8.** Load Reduction by Inter-Zone Air Flow*

Simultaneous cooling and heating

Several established multi-zone system configurations are designed with zonal re-heat. Figure 9A illustrates a typical single duct system with terminal re-heat to one zone. The operation of the cooling coil is determined by the requirement of Zone 1 in this case. As a result, fluctuations in Zone 2 have to be compensated by re-heating. The volume of air supplied to Zone 2 is unnecessarily cooled and then re-heated, resulting in a waste of energy. Mixing of actively cooled and heated air in the system is also inefficient. The dual duct system in Figure 9B is wasteful whenever the cooling and heating coils are required to operate at the same time.

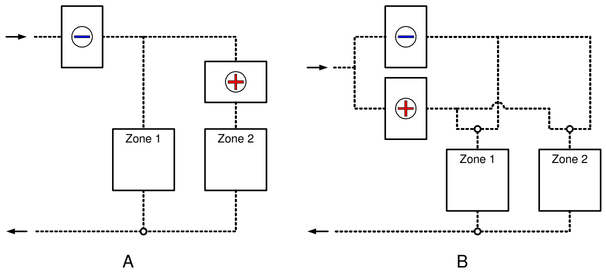

***Figure 9.** Zonal Re-heat and dual-duct system*

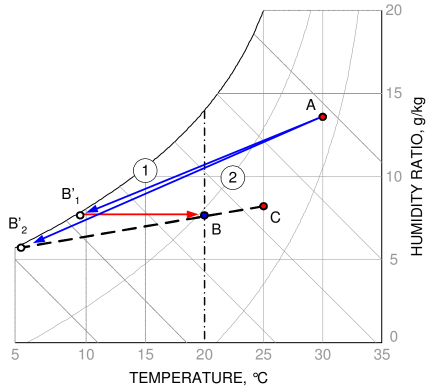

***Figure 10.** Effect of Supply Air Flow Rate and Supply Air Condition*

In order to avoid simultaneous cooling and heating, the operating point of each component in the system has to be optimized, and mixing should be used when possible. The idea of mixing is to make best use of air at its present condition, rather than actively process it to other conditions. Figure 10 shows the psychrometrics of air-conditioning process in summer operation. In order to achieve the required supply air humidity ratio (B), it is necessary to overcool the air to (B1'). Air at (B1') must be re-heated (B1' → B) before being supplied to the zone, which results in simultaneous cooling and heating in the system. The alternative process (2) uses mixing in the place of reheating. The air from condition point A is further cooled to condition B2', which is inline with supply condition B and zone condition C. Then the air at B2' is mixed with C at a ratio about 1:3, to achieve the condition B. Providing the volume of supply air at condition B is the same as in process (1), the volume of air handled by the cooling coil is only ¼ comparing with reheating. This means savings in both cooling and reheating. The principle in process (2) is that mixing should be used whenever it is possible to eliminate active heating, cooling, and humidification.

Optimal configuration

In summary, a conceptual optimal configuration should have the following features:

- Separate air-conditioning for each zone, therefore outside air flow can be minimized.
- Arrangement of zones to minimizing enthalpy difference between inlet and exhaust air.
- Presence of recirculation paths that allow inter-zone load offset.
- Ability to avoid simultaneous heating and cooling in all circumstances.

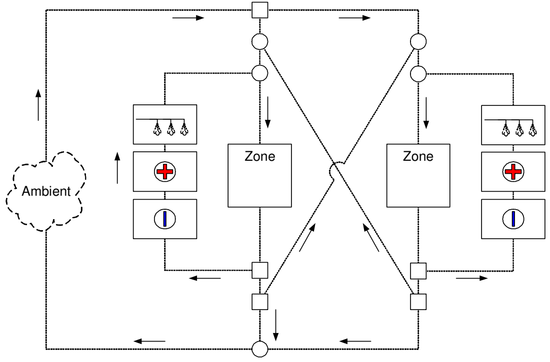

Figure 11. *Fan-coil and fresh air system with inter-zonal flow*

Figure 11 shows the "optimum" configuration for a 2-zone system. The load in each zone is handled individually with fan-coil units. Inter-zone air flow paths are provided to allow re-circulation and mixing. By optimizing the flow rates in each branch, it is possible to exhaust air from either or both of the zones. The performance of the optimum configuration, together with configurations in Figure 1 – 4, is evaluated with an example building.

EXAMPLE BUILDING

The example building used in this study is based on two (E- and W-facing) mid-level zones in a multi-storey building located in Oklahoma City, OK, USA. Both zones have high level of glazing, therefore solar gain is a significant factor. Table 1 gives 6 design operation conditions on 2 design days chosen for summer and winter, respectively. Three hours on morning, mid-day, and evening were selected for each design day. The ambient and design temperature and relative humidity of each zone are provided, as well as the sensible and latent loads. The fresh air demand for the east zone is 0.096kg/s, in contrast to 0.032kg/s for the west zone. The zone sensible loads, however, vary significantly, driven primarily by solar gain. The east and west zone can have different temperature settings at the same time. Therefore, it is possible to save energy with inter-zone air flow and selective exhaust direction.

Table 1. *Design conditions and requirements of the example building*

Data Point		Ambient		East-facing zone (RH=50%)				West-facing zone (RH=50%)			
Time of year	Time of day	Dry bulb temp. (℃)	Relative humidity (%)	Dry bulb temp. (℃)	Sensible load (kW)	Latent load (kW)	Fresh air demand (kg/s)	Dry bulb temp. (℃)	Sensible load (kW)	Latent load (kW)	Fresh air demand (kg/s)
Summer	08:00	29.4	57	20.0	4.391	0.600	0.096	22.0	2.184	0.200	0.032
	14:00	38.9	36	24.0	2.173	0.600	0.096	20.0	5.067	0.200	0.032
	17:00	37.8	37	22.0	1.916	0.600	0.096	20.0	5.545	0.200	0.032
Winter	08:00	-15.6	72	20.0	0.614	0.600	0.096	18.0	-2.023	0.200	0.032
	14:00	-11.1	57	22.0	-0.347	0.600	0.096	20.0	2.601	0.200	0.032
	17:00	-12.2	65	22.0	-0.539	0.600	0.096	20.0	0.639	0.200	0.032

RESULTS AND DISCUSSION

Six configurations from Figure 1 – 4 and Figure 11 (including 2 varieties from Figure 3) have been evaluated using computer models. The performance of each configuration has been optimized using the method described by Wright et al. (2004). The results (Table 2) show that the single-duct and dual-duct configurations perform worse than fan-coil based systems. Both of the centralized systems were unable to minimize the outside air flow in two of the summer conditions. The single-duct system needed simultaneous cooling and reheating during the summer, which resulted in using significantly more energy than others. The two sequentially arranged fan-coil systems work best in some of the conditions but poorly in others. This shows that the direction of exhaust has impact on energy performance. The parallel fan-coil configuration achieved satisfactory performance. The conceptual optimum configuration, however, achieved consistent performance in all design conditions.

Table 2. *Comparison of energy consumption of test configurations*

Data Point		Single-duct (figure 1)		Dual-duct (figure 2)		Fan-coil and dedicated fresh air system						Optimum (figure 11)	
						West -> East (figure 3)		East -> West (figure 3)		Parallel (figure 4)			
Time of year	Time of day	Fresh air (kg/s)	Heating cooling (kW)	Fresh air (kg/s)	Heating cooling (kW)	Fresh air (kg/s)	Heating cooling (kW)	Fresh air (kg/s)	Heating cooling (kW)	Fresh air (kg/s)	Heating cooling (kW)	Fresh air (kg/s)	Heating cooling (kW)
Summer	08:00	0.128	-8.85	0.128	-9.06	0.128	1.47 -10.59	0.128	***-7.31***	0.128	-7.49	0.128	***-7.31***
	14:00	0.243	5.67 -22.40	0.166	-12.07	0.128	***-8.99***	0.128	-9.45	0.128	-9.11	0.128	***-8.99***
	17:00	0.296	1.36 -18.82	0.185	-11.85	0.128	***-9.28***	0.128	-9.50	0.128	-9.32	0.128	***-9.27***
Winter	08:00	0.128	5.77	0.129	5.83	0.128	5.89	0.128	***5.63***	0.128	5.82	0.128	***5.62***
	14:00	0.188	3.86	0.189	3.89	0.176	3.61	0.182	***3.47***	0.176	3.47	0.182	***3.47***
	17:00	0.128	4.10	0.128	4.09	0.128	4.18	0.128	***3.92***	0.128	4.08	0.128	***3.92***

CONCLUSION

As the result of this study, three major factors are identified as having significant impact on the performance of HVAC configurations. These factors are (1) the ability to minimize outside air load; (2) the ability to eliminate simultaneous cooling and heating, and effectively use mixing; and (3) the availability of inter-zonal airflow. A number of configurations have been tested with an example building. Among these configurations, the "optimal" configuration, which has been designed to meet the criteria for good configuration, has shown consistent performance in all test conditions.

ACKNOWLEDGEMENTS

The authors acknowledge funding for this project by ASHRAE under RP-1049.

REFERENCES

ASHRAE, 2000. ASHRAE Handbook – HVAC Systems and Equipment, ASHRAE, 1791 Tullie Circle, N.E. Atlanta, GA 30329, USA. ISBN 0-910110-87-5

Cui Y. Liu M. Conger K. 2003. "Implementation of the Laboratory Air Handling Unit Systems (LAHU)," International Conference for Enhanced Building Operations, October 13 – 15, 2003, Berkeley, California, USA

Song L. and Liu M. 2004. "Optimal Outside Airflow Control of an Integrated Air-Handling Unit System for Large Office Buildings", Journal of Solar Energy Engineering, (126)1:614-619

Wright, J.A., Zhang, Y., Angelov, P.P., Buswell, R.A., Hanby, V.I., 2004. "Building System Design Synthesis and Optimization (Final Report, ASHRAE RP-1049)", Available from ASHRAE, 1791 Tullie Circle, N.E. Atlanta, GA 30329, USA.

Zhang Y. 2005. "Optimal design synthesis for HVAC system configurations", Ph.D. thesis, Loughborough University, Loughborough, Leics. UK