Advanced Distribution and Decentralized Supply: A Network Approach for Minimum Pressure Losses And Maximum Comfort

L. Baldini and F. Meggers
ETH Zurich, Building Systems Group

ABSTRACT

The paper presents a new concept for a low pressure drop supply system suited for the ventilation of office spaces. Lower pressure losses for the air distribution allow a downsizing of the fans cutting down the investment costs for the equipment and the energy consumption during operation. Great potential savings in high-valued energy (exergy) are possible in large buildings where this concept could reduce pressure drops by a factor up to ten. This supply system consists of decentralized air handling units installed near the façade. They feed an interlaced duct network that is integrated in the floor construction. The air is supplied to the room at very low momentum through openings in the floor. Following the low exergy principle the heat exchangers of the air-handling units strictly operate at supply temperatures close to the room temperature, and hence would allow a very efficient operation of a heat pump with a high coefficient of performance. The proposed duct network design eliminates the problem often found in decentralized systems of insufficient air supply to the core of the building. It provides a regular distribution of the air over the entire floor space even in large open plan offices and under non-homogeneous pressure conditions from the wind on the façade or from a locally demand-controlled exhaust system as described by (Baldini and Leibundgut, 2005). As a proof of concept a steady state analysis of the air distribution has been performed for different network topologies. The simulations showed that an effective distribution of the air is possible even for non-homogeneous pressure boundary conditions when the network's topology is close to the one of a mesh. The distribution system is most robust to changing boundary conditions if the topology of the network is such that the velocities within the pipes are small enough to lead to nearly homogeneous static pressures.

1. INTRODUCTION

Climate change forces us to reduce the anthropogenic CO2 emissions significantly in order to limit the danger of more severe natural catastrophes in future. The building sector is with a 38% share of the total primary energy consumption and 34% of the total CO2 emissions world-wide a large contributor to the problem (Price et al., 2006). More than the construction does the operation of the buildings over the entire life-span of 20 to 50 years cause the largest climatic impact. For this reason HVAC systems must be improved to minimize environmental impact during operation. There is still a large potential in actual HVAC systems for improvements concerning energy consumption as well as cost effectiveness. New concepts have to be introduced to exploit these potentials. The current paper proposes a new ventilation concept from which significant energy savings are expected.

Nowadays heat recovery for ventilation in office buildings is common practice and helped reducing ventilation losses significantly. Further reductions are possible by decoupling the ventilation from the heating or cooling needs.

This is very common in Europe while in the US or in most Asian countries air-conditioning is still the predominant approach to satisfy comfort needs. The decoupling allows very low ventilation rates to be used, to just satisfy the indoor air quality (IAQ) requirements. When making these improvements it is important also to consider distribution losses of the ventilation that now become even more relevant. The issue of pressure losses during distribution is hardly addressed explicitly in literature. Most of the studies found restrict their scope to general energy evaluations of ventilation systems without identifying the origin of the losses. Pressure losses in ducting systems directly relate to fan power and therefore to losses of high grade energy, usually electricity.

2. DECENTRALIZED VENTILATION CONCEPT

If ventilation is only used to assure a good IAQ and not for temperature control, relatively low ventilation rates are necessary and alternatives to strictly centralized concepts become an opportunity.

The decentralized supply concept described herein follows the principle of displacement ventilation and benefits from larger ventilation efficiencies compared to mixing systems (Skistad, 1994). It works similarly to classical underfloor air distribution (UFAD) systems and hence also profits from advantages of these systems (Bauman and Webster, 2001). Major differences to UFAD as commonly used in the US are the supply of fresh air from the façade with a high number of decentralized supply units and the use of a ducting network integrated in the slab construction instead of using a pressurized raised floor. The networked structure connects the different supply units such that pressure differences between different sides of the façade can be balanced.

Decentralized air handling units are more and more finding their way into modern office buildings in Europe. Especially in Germany, large projects with decentralized air supply were realized. Most air handling units used rely on small radial fans using a constant flow rate control guaranteeing the design flow rate up to pressure differences around +/- 200 Pa. In contrast to the constant flow rate control this paper presents an alternative approach that exploits the distribution means to cope with different wind pressure situations.

3. METHODS

3.1 Evaluation of Pressure Drops in Ventilation Systems

Swiss standards (SIA V382/3) require the pressure drop for ventilation systems including supply and exhaust to be below 1200 Pa with flow rates around 30 m^3/h per person recommended. At least half but rather more of the total pressure drop occurs on the supply side. Radial fans of different blade designs with belt drives are most commonly used.

For the analysis of the proposed decentralized supply system and its comparison to regular, centralized supply systems a simple square building with five floors and a floor space of 400 m^2 per floor has been defined. A specific ventilation rate of 4 $m^3/(h\ m^2)$ was assumed.

To overcome the situation of lacking information concerning pressure drops in typical, centralized, mechanical ventilation systems, commercially available radial fans from different suppliers have been analyzed for a given flow rate to estimate realistic pressure drops. It has been found that suitable fans for a flow rate of 8000 m3/h according to the previously defined reference building, have a total pressure rise around 800 Pa when working with maximum efficiency. The most efficient fans with fan efficiencies around 80% are those using backward inclined blading.

The assessment of the pressure drops in the decentralized supply system has been done using static pressure values calculated in a simulation of the supply network as described in the following.

3.2 Simulation of Air Distribution in a Decentralized Supply Network

The distribution of the flow rates in the decentralized supply system were analyzed using an adapted one dimensional, steady state formulation of the mass and energy conservation principle for compressible flows. A nodal formulation together with a damped

Newton-Raphson method was used to solve for static pressures in the network nodes. Nodes can be junctions, openings or fans. The mass flows in the pipes where calculated using a simplified equation based on an equation derived by (Osiadacz, 1987) for isothermal flow.

$$p_1^{\ 2} - p_2^{\ 2} = \frac{16\lambda R T_s L}{\pi D_h^{\ 5}} \dot{m}_n^{\ 2}$$

p1, p2: Nodal pressures
λ: Dimensionless friction factor
R: Specific gas constant for air
T_s: Temperature of the supply air
L: Pipe length
D_h: Hydraulic diameter
$\dot{m}_n$: Mass flow evaluated at T_n=293°K and p_n=1e5 Pa

Additional assumptions of an ideal gas and zero elevation were made. For the calculation of the mass flow major and minor losses were considered. Loss coefficients for a sudden contraction and expansion as found in many text books such as (Wilcox, 1997) have been introduced for all nodes. Openings also include a loss coefficient for the exhaust into the room. The fans use an additional loss coefficient for the intake through a protection grating in the façade. For the fan characteristics a 2nd order polynomial has been implemented.

As Global input parameters to the simulation ambient pressure of 1e5 Pa and ambient temperature of 273 °K were used. The supply air is assumed to be at a temperature of 293 °K with a specific gas constant of 287 J/(Kg K) and a dynamic viscosity of 1.8e-5 kg/(m s).

3.3 Procedure of Analysis

The supply units assumed are similar to devices that have been developed in a collaboration between the Building Systems Group at the ETH and industry and have a nominal flow rate of 100 m^3/h if no external pressure difference is applied. The coefficients of the fan characteristics are listed in Table 1. 18 fans have been used in the simulation to be able to reach the design flow rate of 1600 m^3/h per floor. Parameters of other components selected such as pipes and openings are shown in Table.

Table 1: Parameters of components used in simulation

Pipe:	
Hydraulic diameter	0.118 m
Roughness	7e-3 mm
Junction:	
Hydraulic diameter	0.177 m
Opening:	
Hydraulic diameter	0.177 m
Exhaust loss coeff.	5.39
Fan:	
Hydraulic diameter	0.195 m
Inlet loss coeff.	10
Fan coefficient A	-3.566e4 $Pa/(m^3/h)^2$
Fan coefficient B	-0.243e4 $Pa/(m^3/h)$
Fan coefficient C	97 Pa

An appropriate topology of the air distribution network has been defined for the analysis of the air distribution. In the generation of the topology, it was avoided to have openings connected in series because it leads to an uneven distribution of flow rates between the openings. The resulting topology of the distribution network with 18 fans, 24 openings and 14 junctions is shown in Figure 1a. A very simple, unconnected topology with 18 fans and 18 openings has also been defined to be used as a reference case for the discussion of the results. This topology represents a classical way of connecting decentralized supply units and is shown in Figure 1b.

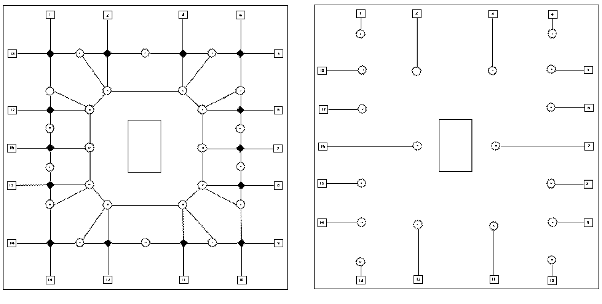

Figure 1: a. network topology, b. unconnected topology

The squares in Figure 1 represent the fans, the circles the openings and the black diamonds the junctions.

Two different cases, without and then with wind loading were studied. The same dimensionless external averaged pressure coefficients as implemented in the tool called WeatherSmart (Djebbar, 2001) based on a trigonometric function developed by (Walker and Wilson, 1994) were used to derive pressure differences from the wind loading around the building. Pressure differences were applied at the fan locations along the façade as boundary conditions for the simulation in case of wind impact. For the evaluation of the pressure differences using the pressure coefficients, an average wind speed of 6 m/s was assumed (MeteoSchweiz, 1982-2000). A more severe wind loading with 10 m/s wind speed was also considered in the analysis. For the simulations of the air distribution an open plan situation was assumed. In the discussion of the results, a virtual separation was introduced to highlight problematic areas such as separated rooms located at the corner of the downwind side of the building. The assessment of the supply system and its effectiveness in air distribution is based on the flow rate supplied at each opening.

4. RESULTS AND DISCUSSION

4.1 Pressure Drops and Energy Savings

The largest pressure drop recorded in the distribution network for the case of no wind loading is 12.7 Pa. This is the pressure that the fans have to overcome in the supply network. Additionally to this pressure a pressure drop in the decentralized supply units of 40 Pa have to be considered. The total pressure drop in the supply system when rounded up is about 55 Pa. The small axial fans used in the supply unit have an overall efficiency depending on the operation point around 20 %. In centralized systems the fan efficiency of large radial fans such as described previously is around 80%. In order to derive the total efficiency, the losses of the belt drive of typically 5% (Lexis, 2000) and the efficiency of the electrical motor of typically 90% (Lexis, 2000) have to be considered. Equating these losses and efficiencies a final total efficiency around 70% results. For the comparison of the electrical fan power consumption the 800 Pa pressure drops and the total efficiency of 70% of the centralized supply system have to be confronted with the 55 Pa and 20 % efficiency of the decentralized system. In the case of using this decentralized supply system instead of a centralized one, fan power can be reduced by that factor 4.16. This leads to tremendous energy savings when cumulated over the life-span of the plant and reduces running cost of the building significantly.

4.2 Evaluation of Flow Rate Distribution

The estimated probability density functions for the distribution of the flow rates are displayed in Figure 2 and Figure 3.

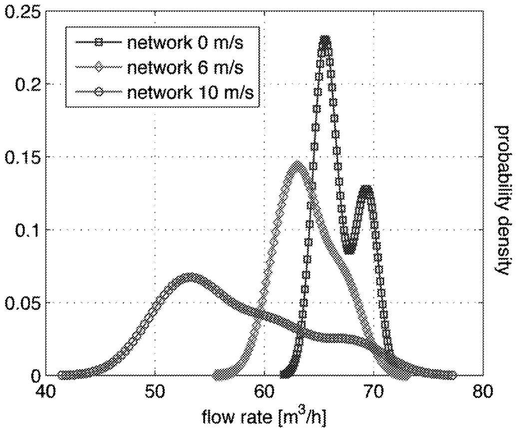

Figure 2: Flow rate distribution in the network

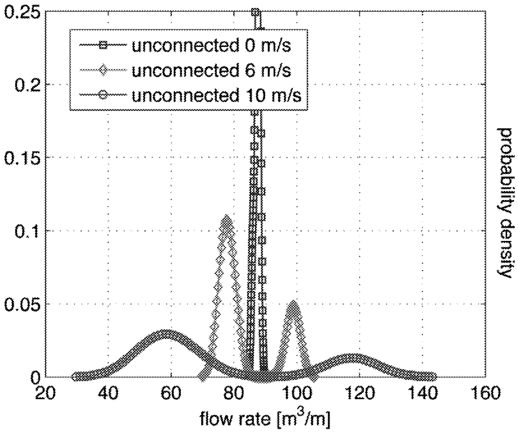

Figure 3: Flow rate distribution in the unconnected topology

Three density curves are shown for no wind loading and for wind loading with 6 and 10 m/s wind speed. The unconnected case Figure 3 has a larger mean flow rate than the network Figure 2 because of fewer openings. The net flow for both topologies is however almost the same since there is always the same power input from the fans. The decrease of the net and the mean flow with wind depends on the fan characteristics and is hence the same for both topologies. -4.3% for 6 m/s and -14% for 10 m/s wind speed respectively. The respective net pressures acting on the buildings envelope for those wind speed are -5.23 Pa and -14.54 Pa.

For the case of no wind loading the unconnected topology shows the most homogeneous distribution of the flow rates with a standard deviation of 0.66 m^3/h because the pressure drops in the pipes are very low such that only small pressure differences between the different branches occur. In the network case there are two peaks in the density function. The smaller peak to the right is due to the higher flow rates in the corners of the network. This fact is also reflected in the increased standard deviation of 1.94 m^3/h.

For the case of wind loading with 6 m/s wind speed the unconnected topology shows two very clearly separated peaks in the density function. This reflects the wind loading with positive pressures on the windward side of the building and negative pressures on all the others sides. A similar picture is observed for a wind loading with 10 m/s only that there is a much larger spread in between the flow rates. For the network a much more uniform picture appears for the case of wind loading. At a wind speed of 6 m/s the density function has a slightly increased standard deviation but the second peak to the right that could be observed in the case of no wind loading disappeared. This indicates that at the junctions in the corners the excess flow rates where reduced due to the negative pressure boundaries. For wind speeds of 10 m/s the flow rates are clearly spread over a larger range of values but compared to the unconnected case there is still a much more uniform picture. No distinct peaks can be observed in the network and the standard deviation is with 6.06 m^3/h much lower than 27.34 m^3/h in the unconnected case.

Other measures were used to asses the quality of distribution of the two topologies and their sensitivity to wind loadings. Figure 4 shows the relative deviations of maximum and minimum flow rates from the mean flow rate for each case. This is a another measure of the spread of flow rates and expresses the quality of distribution. The slopes of the curve are a measure for the sensitivity of the system to wind loading. The ideal distribution would have only one value for the flow rate, i.e. zero deviation and a slope of zero.

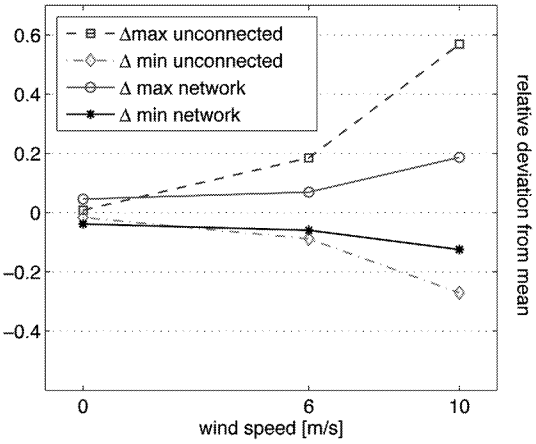

Figure 4: Relative deviations of min, max from the mean flow rate

As already mentioned is the spread between minimum and maximum values in the case of no wind the smallest for the unconnected topology. This changes dramatically with wind impact. A strictly larger spread for the minimum as well as the maximum values is observed for the unconnected topology. Most interesting to note is the expressed difference of deviations of the maximum values between the two topologies. The significantly lower increase of the maximum flow rates relative to the decreasing mean value again shows the effective distribution of flow rates in the network from higher toward lower values. This is also confirmed by the lower decrease of the minimum values in the network despite the fact that the mean value and the total net flow rate decreases in the same way for both topologies.

For a more severe wind loading with 10 m/s wind speed significant deviations for minimum and maximum flow rates are observed for both topologies. At that point one must recall that the simulations where all performed for a 0 Pa relative pressure boundary on the inside of the building. This means, it is assumed that the exhaust flow rate is adapted to the supply flow rate in a perfect sense such that no pressure difference due to incontinuities appear. In reality the exhaust would be constant, adjusted by coupling with the supply units or pressure controlled but with some limits to resolution. If the exhaust rate is kept constant while the supply rate decreases a negative pressure builds up in the room. This situation can be simulated by applying a negative pressure boundary condition in the inside. For this purpose a virtual separation was introduced. It shall represent an office which is separated from the open plan situation. This separation was chosen in the most critical corner to the right in Figure 1a if it is assumed that wind is hitting the building from the left side. For that situation negative pressures occur on both sides of the façade. The separated area comprises 4 fans and 5 openings of the network. A negative pressure of -1 Pa was applied for the 5 openings lying within the virtually separated room and a wind speed of 10 m/s was assumed. The cumulated flow rate of the five openings lies only 5.5% below the value for no wind loading. When 0 Pa inside pressure is assumed as in the previous simulations the decrease of the cumulated flow rate is 18.8%. This ability of the network to redistribute the supply air between different zones with minute pressure differences is the major strength of this approach. It insures that only very small pressure gradients can build up between different rooms or zones. For the unconnected topology this of course does not hold. The only way to compensate for flow rate being to low is to fully compensate for the pressure difference applied by the wind.

5. CONCLUSIONS

As could be seen in the comparison presented, the decentralized supply system offers a possibility for tremendous energy savings in terms of fan power. A theoretical reduction of fan power by the factor 4.16 was estimated for a flow rate of 8000 m^3/h when compared to a centralized supply system. Concerning the air distribution it could be shown that a ducting network in contrast to a classical, unconnected topology allows a adequately regular distribution at least for relatively small wind speeds up to 6 m/s. For higher wind speeds significant deviations also in the network occur if a zero pressure boundary condition at the inside of the building is applied. For a more realistic case with slight negative pressure in the room the analysis of a virtual separation has shown that even for a wind speed of 10 m/s a local availability of the flow rate in the separated room of 94.5% could be achieved. This highlights the ability of the ducting network to distribute air with very low pressure drops which is the major strength of this network approach and differentiates it from the commonly used unconnected topologies.

6. OUTLOOK

More work is needed in the assessment of other topologies and their flow rate distribution characteristics to be able to identify key parameters for a more general topology optimization. A more in depth analysis of potential energy savings when using the wind for air transportation is needed. This includes the use of more realistic wind loadings, the analysis of suitable control strategies as well as a definition for the level of fan overcapacity needed. The overcapacity of fans increases the degree of freedom for further optimizations concerning energy savings based on outside pressures or temperatures.

REFERENCES

Baldini L. & Leibundgut HJ. (2005). Increasing the Effectiveness of Building Ventilation Systems Trough Use of Local Waste Air Extraction, Proceedings of Clima 2005, RHEVA World Congress, Lausanne, Switzerland

Bauman F. & Webster T. (2001). Outlook for Underfloor Air Distribution, ASHRAE Journal, Vol. 43, No. 6,

Djebbar, R., van Reenen, D. and Kumaran, M.K (2001). Environmental Boundary Conditions for Long-term Hygrothermal Calculations, Proceedings for Performance of Exterior Envelopes of Whole Buildings VIII: Integration of Building Envelopes, December 2-7, Clearwater Beach, Florida.

MeteoSchweiz (1982 - 2000). Swiss Federal Office of Meteorology and Climatology. Wind Statistics for the location of Zurich, Switzerland

Osidiacz A. J. (1987). Simulation and Analysis of Gas Network, London: E. & F. N. Spon Ltd

Price L., et al. (2006). Sectoral Trends in Global Energy Use and Greenhouse Gas Emissions. Lawrence Berkeley National Laboratory, Paper LBNL-56144.

SIA V 382/3 (1992). Bedarfsermittlung für Lüftungstechnische Anlagen, Swiss Standards

Skistad H. (1994). Displacement Ventilation, Taunton: Research Studies Press

Walker I. S. & Wilson D. J. (1994). Practical Methods for Improving Estimates of Natural Ventilation Rates, 15th AIVC Conference Proceedings Volume 2

Wilcox D. C. (First Edition) (1997). Basic Fluid Mechanics, La Cãnada: DCW Industries, Inc.