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THE “FAMILY TREE” OF AIR DISTRIBUTION SYSTEMS

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Abstract

In this paper all total volume air distribution principles are addressed based on discussions of air flow pattern in a room with heat sources giving a cooling load. The supply and exhaust air openings are considered to have different locations and sizes in the room, and it is possible to show that all the known types of air distribution systems are interconnected in a “family tree”. The influence of supplied momentum flow versus buoyancy forces is discussed, and geometries for high ventilation effectiveness are indicated as well as geometries for fully mixed flow. The paper will also show conditions which are not used for air distribution in general.

A number of experiments with different air distribution systems are addressed, and they illustrate the behaviour at the different conditions discussed in the paper.

Keywords: Air distribution, mixing ventilation, vertical ventilation, diffuse ceiling inlet, displacement ventilation, clean room.

The family tree of room air distribution principles

It is known from the similarity principles that the air distribution in a room with fully developed turbulent flow can be described unambiguously by the Archimedes number, which can be considered as the ratio between the buoyancy force and the momentum force, Goodfellow and Tähti (2001). The Archimedes number can be expressed as $Ar \sim \Delta T_o / u_o^2$ or as $\Delta T_o / q_o^2$ because the supply area a_o is constant in a given geometry, ΔT_o is the temperature difference between return and supply, u_o the supply velocity and q_o the supply flow rate. Apart from the Archimedes number, several boundary conditions including geometry, supply and return air openings, different sources and sinks of heat load including their strength and location, enclosure surface temperature, etc. have influence on the air distribution in spaces. It can be very complicated to describe all details of the boundary conditions because they are individual for different rooms, but a few primary and common parameters shall be considered. The ratio between the total area a_o of the supply openings and the surface area A of wall/ceiling/floor in which the supply openings are located, a_o/A , is an important parameter for the air distribution in the room. At a given supply flow rate, the momentum flux of the flow from the openings controls the air movement if a_o/A is small, while the thermal plumes from heat sources control the air movement in the occupied zone if a_o/A is large and the air change rate is moderate. It is possible to obtain a unidirectional flow in the room if a_o/A is equal to 1.0.

The location of the air supply and air exhaust openings in relation to the direction of gravity is also important. A high location of the air supply opening will in some cases give a different air distribution pattern than a low location of the air supply opening. Furthermore, the location of the air exhaust opening can also be important for the ventilation effectiveness, see Mundt et al. (2004).

The primary variables describing the flow in a room are therefore:

- Cooling mode or heating mode
- Archimedes number $\Delta T_o / q_o^2$, or flow rate of air supplied to the room, q_o and temperature difference between return and supply air, ΔT_o
- The ratio between the total area of the supply openings and the wall area, a_o/A
- Location, high or low, of the air supply opening(s)

The ratio, a_o/A , is considered to be small for values smaller than 10^{-3} , medium for 10^{-2} , and large for values close to 1.0. The values smaller than 10^{-3} are typical for diffusers designed for mixing ventilation, and the value $6 \cdot 10^{-3}$ is typical for displacement ventilation diffusers. Large ceiling mounted diffusers for vertical ventilation have an area ratio around $3 \cdot 10^{-2}$. The ratio 1.0 corresponds to supply through the whole ceiling, wall or floor, providing the possibility of a piston flow dependent on the level of the momentum flow and direction and level of buoyancy force.

In the cooling mode, the air distribution pattern in a room can be addressed in a three-dimensional chart defined by the flow rate supplied to the room, q_o , the difference between exhaust and supply air temperature, ΔT_o , and the ratio between the total area of the supply openings and the wall area, a_o/A as shown in Figure 1.

The whole family of air distribution patterns can in the case of cooling be described in two three-dimensional charts, “family trees”: one for a high location of the supply opening and one for a low location of the air supply opening (Nielsen 2009). This presentation will address the interconnection between the different systems, indicate the possibility for new development, and the discussion is based on fluid dynamics principles, measurements made in the laboratory during a number of years, and CFD predictions.

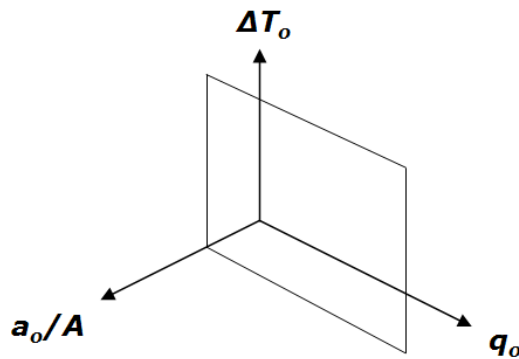


Figure 1. Three-dimensional chart which defines the room air distribution.

The variables in Figure 1 can also address a design graph for the room air distribution. Figure 2 shows such design graph ($q_o - \Delta T_o$ graph) for a constant value of a_o/A . The lower right side of the section defines momentum driven flow while the upper left side defines a flow driven by the buoyancy forces. The curve indicates the position of the critical Archimedes number where the air movement changes between the two different types of flow.

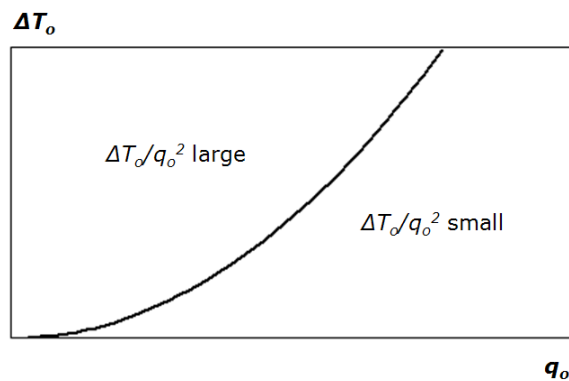
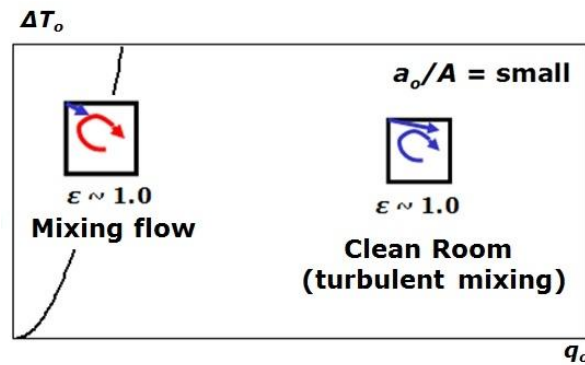


Figure 2. Determination of airflow in a room with a given a_o/A ratio based on the critical Archimedes number. Stratified flow or large mixing effect can take place in the left side of the graph while large mixing effect can take place at the right side of the graph due to high supply momentum.

Mixing ventilation

Mixing room air distribution aims for diluting polluted and warm room air with a cleaner and cooler supply air. The air is supplied to the room with high initial mean velocity and the established velocity gradients generate high turbulence intensity, which promotes good mixing and uniform temperature and pollution distribution in the occupied zone. Mixing ventilation is also called an air distribution pattern with mixing effect or mixing air distribution.



Mixing ventilation with a high location of the diffuser (Lindab A/S).



Clean room mixing flow
(Institute for Science and International Security)

Figure 3. Graph showing mixing ventilation with a high location of the air supply openings. Clean room technology with a high turbulent flow is also indicated in the q_o - ΔT_o chart. The two lower photos show a meeting room with a ceiling mounted swirl diffuser, and a clean room with turbulent mixing diffusers, respectively.

The chart in Figure 3 indicates how the air distribution pattern with mixing effect is generated by diffusers supplying a high momentum flow to the room. To obtain this high momentum flow at air change rates of 1 to 5 h^{-1} , it is necessary to have diffusers with small openings (small a_o/A). The supply air velocity is high and diffusers are therefore located outside the occupied zone of the room as shown in the photos. Entrainment of the room air by the supplied jets creates a high mixing in the occupied zone and a ventilation effectiveness of ~ 1.0 is achieved. The air supply openings can in principle have any location outside the occupied zone. As already defined, two types of air distribution, namely air distribution based on a buoyancy effect (large ΔT_o and relatively small q_o) and air distribution driven by momentum of the supplied flow (large q_o), can be achieved as illustrated in the graph in Figure 3 although the momentum driven flow is the general situation for a small a_o/A .

Similar examples of air distribution patterns with mixing effect are given by Nielsen (1980) and Nielsen et al. (2003 and 2006).

The ΔT_o - q_o chart in Figure 3 also identifies an area which is a clean room with a very high supply flow rate and turbulent mixing. The photo in Figure 3 shows an example of such a room.

Vertical ventilation

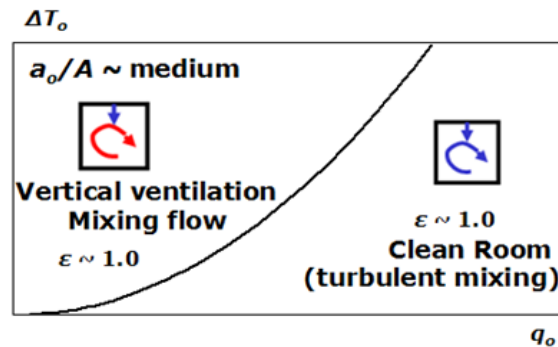
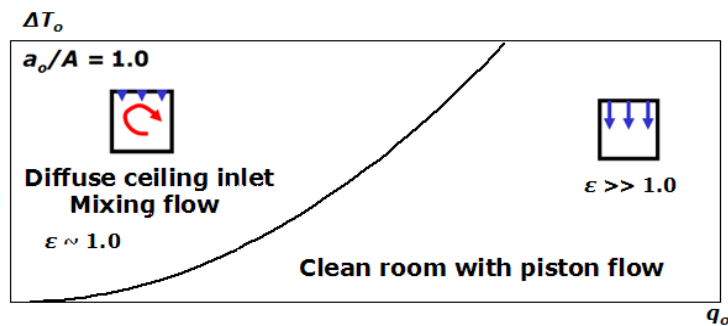


Figure 4. Vertical ventilation from openings in the ceiling. $a_o/A \sim$ medium. The photo shows this type of flow from ceiling mounted textile terminals (KE Fibertec A/S).

The air distribution in rooms with vertical ventilation from openings with a medium area in the ceiling, a_o/A , will be controlled by the thermal forces (large $\Delta T_o/q_o^2$), see Figure 4. It is important that that cooling is the common situation to avoid stratification, which will take place in case of heating. The flow in the room will show a high level of mixing effect when the heat sources are located below the diffusers, but there will also be some displacement effect when the diffusers are located outside the heat sources as shown by Nielsen et al (2007). This air distribution system can therefore in most cases be considered as a mixing ventilation system. A q_o - ΔT_o chart for vertical ventilation with $a_o/A = 0.03$ are given by Nielsen et al. (2006).

High momentum mixing flow with medium opening areas in the ceiling (see Figure 4 at the right of the chart), is also considered as clean room mixing ventilation based on a highly turbulent flow.

Diffuse ceiling inlet



Diffuse ceiling inlet (Wessberg).



Clean room with piston flow (Shelco Inc).

Figure 5. Diffuse ceiling inlet and unidirectional clean room flow. $a_o/A = 1.0$. The two lower photos show an office with diffuse ceiling inlet and a clean room with piston flow and high flow rate, respectively.

Air distribution pattern in rooms with diffuse ceiling inlet, i.e. where the whole ceiling is the supply opening ($a_o/A = 1.0$) might be controlled either by buoyancy flows from heat sources (large $\Delta T/q_o^2$) or by momentum flow, Figure 5. In the case of air distribution pattern controlled by buoyancy flows, the ventilation effectiveness is around 1.0 (air change rate equal to 1 – 5 h^{-1}). A high load can be handled without significant draught, because the draught is generated by the heat sources and not by the momentum flow from the supply openings. This air distribution system could also be defined as a mixing ventilation system because the ventilation effectiveness is close to one. This type of air distribution pattern is described by Nielsen et al. (2009). The use of preheating after night setback is studied, Nielsen et al. (2010). A systematic study of large ceiling inlet ($a_o/A = 1.0$) with different flow rates is made by Linke (1962).

At high air change rates, 50 – 100 h^{-1} , piston flow takes place, and the system is a clean room air distribution system with very high ventilation effectiveness. Low location of the return openings is required in this case.

Displacement ventilation

Displacement ventilation is called an air distribution pattern with displacement effect or displacement air distribution. Displacement ventilation takes place when the thermal flows from the heat sources are controlling the air movement in the room (large $\Delta T/q_o^2$). The supply openings are normally located at a low level (on a wall or in the floor) and the return openings are located just

below the ceiling or in the ceiling. Displacement air distribution aims to replace but not to mix the polluted room air with clean air. The clean and cool air is supplied close to the floor at low velocity. Therefore, in rooms with displacement air distribution, the highest velocity and the lowest temperature occur near the floor (approx. 0.05 m above the floor). Unlike in rooms with mixing ventilation, vertical temperature gradient exists in a room with displacement ventilation.

The opening supply areas are large (medium a_o/A) and the supplied flow has low momentum at normal air change rate of 1 to 5 h^{-1} , and it is therefore irrelevant for the room air distribution compared to the flow driven by buoyancy effect, Figure 6. The flow may be thermally stratified in the occupied zone, and it is possible to work with a ventilation effectiveness larger than 1.0. Displacement ventilation is described in the REHVA Guide book no. 1, Skistad et al. (2002). Displacement ventilation achieved with underfloor air distribution at relatively high supplied airflow momentum is described by Bauman (2003). This type of displacement ventilation gives similar air distribution pattern in the room as conventional ventilation.

High flow rate and medium supply area as shown in the right side of the chart (Figure 6) is normally not a practical solution for an air distribution system because high velocities will be generated in the occupied zone.

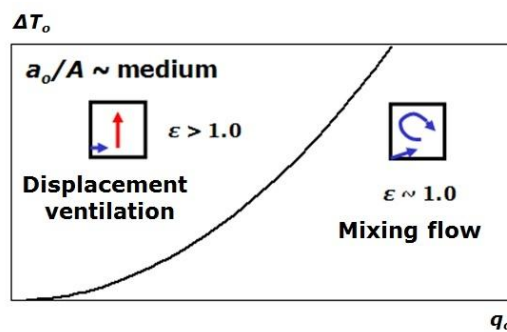


Figure 6. Displacement ventilation. The supply openings are located at a low level, and the return openings are at a high level. The opening supply area is relatively large. The photo shows displacement ventilation diffusers in a restaurant (Lindab A/S).

Diffuse floor inlet or supply through the carpet is a version of displacement ventilation where a_o/A is equal to 1.0, see Figure 7. In this case, the air distribution pattern with displacement effect is driven by buoyancy forces (upper left side in the chart, Figure 7). This principle has high ventilation effectiveness. High momentum unidirectional flow from the floor, as shown on the right side of the

graph in Figure 7, is not used in practice in clean room because it will not ensure clean air in the working zone in the room.

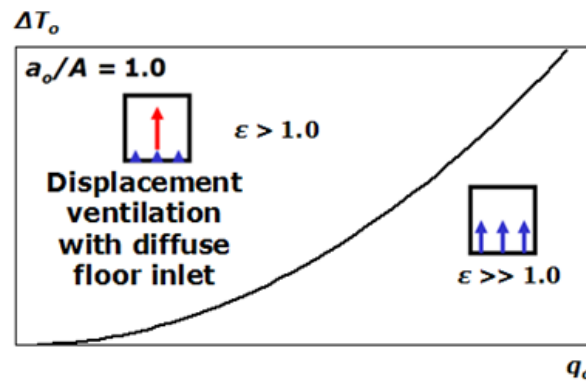


Figure 7. Displacement flow with diffuse floor inlet. $a_o/A = 1.0$. The photo shows the Reichstag in Berlin with supply air flow through the carpet.

A study of diffuse ceiling or floor inlet ($a_o/A = 1.0$) by Linke (1962) shows air distribution patterns at different flow rates which is in accordance with the results shown in this work.

The family tree of air distribution

The whole “family” aspect of air distribution patterns can in the case of cooling be described in two three-dimensional charts, “family trees”: one for a high location of the supply opening and one for a low location of the air supply opening, respectively. The charts are shown in Figures 8 and 9 (Nielsen 2009).

High location of the air supply openings makes it difficult to work with stratification effects and to obtain high ventilation effectiveness in the case of cooling (Figure 8). Most of the flow is characterized by a strong mixing, either due to the high momentum of the supplied airflow or due to the interaction of the supplied cold flow moving downwards with the upward thermal plumes generated by heat sources. Thus ventilation effectiveness of approx. 1.0 is typical for this air distribution patterns. Only in the case of downward flow from diffuse ceiling inlet ($a_o/A = 1.0$) and high flow rates, the established piston flow makes it possible to obtain a very high ventilation effectiveness, and this is a convenient way to supply clean air to the working zone in a clean room.

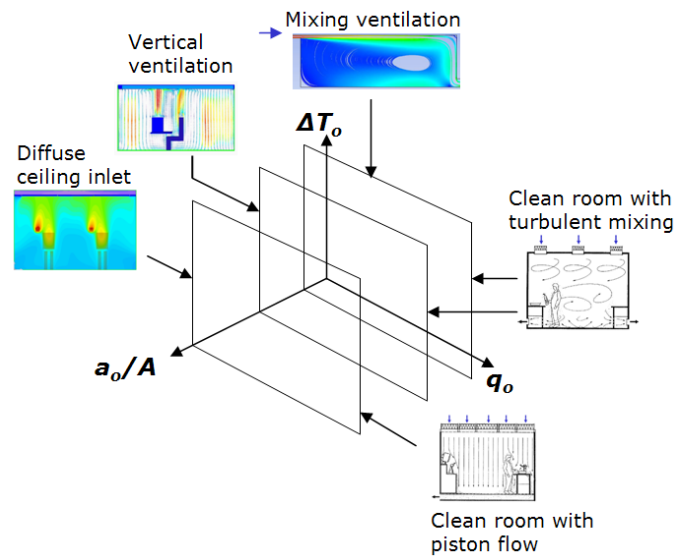


Figure 8. Different air distribution systems for cooling with high location of supply openings. The figure is a three-dimensional expression of the Figures 3, 4 and 5.

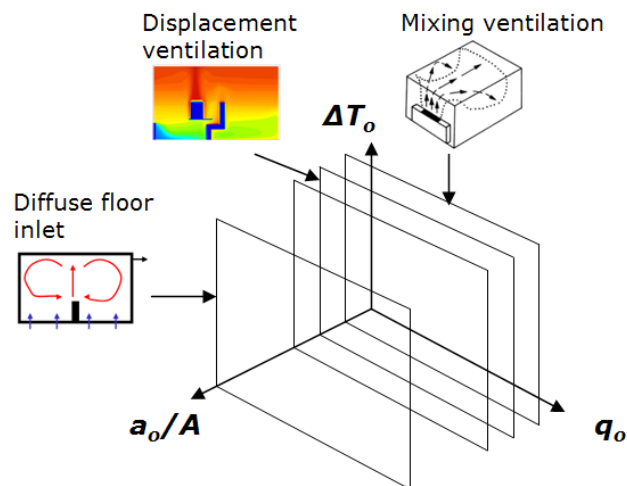


Figure 9. Different air distribution systems for cooling with low location of supply openings. The figure is a three-dimensional expression of the Figures 6 and 7.

Air distribution with mixing effect can be achieved with small supply openings located at low room height. It is important that the region of the generated flow with high velocity is outside the occupied zone (Figure 9). Low location of the supply openings makes it possible to work with high ventilation effectiveness because the stratification effect can be used and displacement air distribution can be achieved. This is especially the case when the openings are large and therefore have low momentum flow. High location of return openings is required in those cases.

The design chart for an air distribution system

One of the aims of the design of an air distribution system is to find the limits regarding possible flow rates into the room and temperature differences between the supply and return temperatures, i.e. to find the limits that maintain an acceptable comfort level with small draught and low temperature gradients in the room. To make the decisions more qualified, a design chart is developed; see (Nielsen, 1980 and Nielsen, 2007). The design chart (q_o - ΔT_o) is a part of the family tree, and it has been utilized to evaluate several ventilation principles. By using the design chart, it becomes possible to compare different systems and enables the user to find the best system for individual demands.

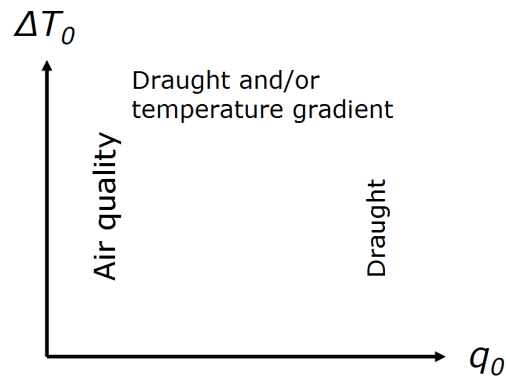


Figure 10. Design chart that indicates the restrictions on the flow rate q_o and on the temperature difference ΔT_o between return and supply.

Figure 10 describes the idea behind a design chart for air distribution in rooms. The chart is based on the minimum and maximum allowable flow rate q_o to the room, and also on the maximum temperature difference between return and supply. The figure indicates that it is necessary to have a minimum flow rate of fresh air into the room in order to obtain a given air quality. This flow rate is constant and independent of ΔT_o when the air distribution system generates mixing, but it can be a modest function of ΔT_o in the case of displacement ventilation. It is characteristic of air distribution systems based on the momentum flow supply that they generate a mixing in the occupied zone, which is important for the creation of uniform conditions in the occupied zone when the heat load is high. There is a drawback to the systems, namely that this flow generates draught when the flow rate is above a certain level.

Some systems, such as diffuse ceiling inlet, generate a very low level of momentum flow and, therefore, they do not show a limit of q_o . Draught is in this case generated by the heat loads in the room, which limits the product of q_o and ΔT_o (thermal load).

The temperature difference ΔT_o between return and supply is also restricted as indicated in Figure 10. A too high temperature difference may either cause draught in the occupied zone or create a too large temperature gradient in the room.

Figure 10 indicates an area for the variables q_o and ΔT_o , which will give a sufficient supply of fresh air, and a draught free air movement in the occupied zone, plus a restricted vertical temperature gradient. This area is considered as the design area for a given air distribution system. The limits for the design area are in the following defined as a maximum air velocity of 0.15 m/s in the occupied zone, a maximum vertical temperature gradient of 2.5 K/m and a minimum flow rate of 10 l/s per person.

Six air distribution systems are addressed in the following, namely; mixing ventilation from a wall-mounted terminal, mixing ventilation from a ceiling-mounted diffuser, mixing ventilation from a ceiling-mounted diffuser with a swirling flow, displacement ventilation from a wall-mounted low velocity diffuser, a low impulse system based on ceiling mounted textile terminals and a diffuse ceiling inlet. The systems are all tested in the same full-scale room. The dimensions of the room are in

accordance with the requirements of the International Energy Agency Annex 20 work with length, width and height equal to 4.2 m, 3.6 m and 2.5 m, respectively, see Figure 11.



Figure 11. Furnishings and heat load of the IEA Annex 20 room (office layout). The heat load consists of two PCs, two desk lamps and two manikins producing a total heat load of 480 W.

The thermal load is constant in all experiments, and the air change rate has been varied from 2.75 h^{-1} up to 10.45 h^{-1} with a variation in the temperature difference ΔT_o between 12 K and down to 3.5 K. The room temperature is close to 22.9°C in all the experiments.

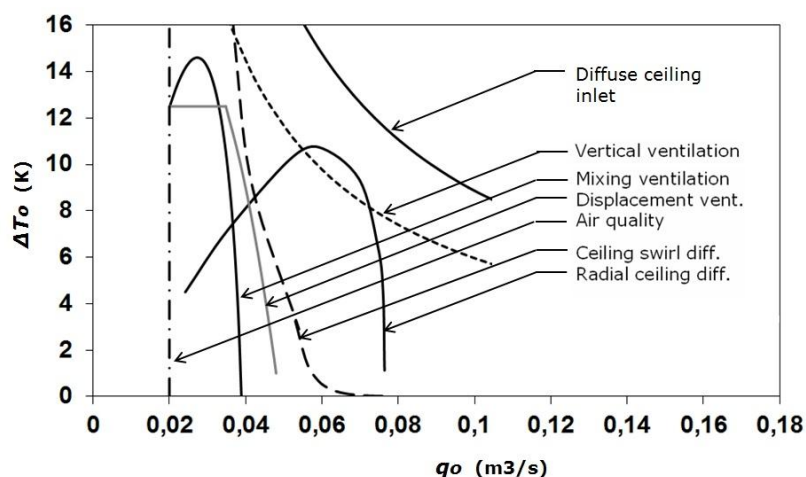


Figure 12. Design chart for the six different air distribution systems. Air quality requires that q_o is larger than $0.02 \text{ m}^3/\text{s}$.

Figure 12 indicates that to some extent the room has the same level of comfort (in terms of maximum velocity and temperature gradient) in the case of mixing ventilation with a wall-mounted diffuser or displacement ventilation with a wall-mounted low velocity diffuser. The figure also shows that the vertical ventilation (low impulse) systems, and especially diffuse ceiling inlet, are superior to both mixing ventilation based on a wall-mounted diffuser and to displacement ventilation (the $q_o - \Delta T_o$ curve is located to the right of the curves of the three other systems).

Mixing ventilation generated by diffuse ceiling inlet is able to handle a higher heat load than any of the other systems. This is indicated in Figure 12 with a $q_o - \Delta T_o$ curve located above and to the right of the curves of the other systems.

It should also be emphasized that the design chart, Figure 12, to some extent could be dependent on room size, room layout and layout and design of the terminal units (number, location, etc.).

Conclusions

The flow in a room with internal heat sources and with supply and exhaust openings with different locations and sizes can be arranged in a “family tree”. Five different types of air distribution systems can be identified, and they are:

- Mixing air distribution
- Vertical air distribution
- Diffuse ceiling inlet
- Displacement air distribution
- Clean room with piston flow

Mixing ventilation can either be defined as a system with small supply openings, a_o/A , giving a high mixing flow in the room, but it can also be a system with larger openings at high location where the mixing effect is created by buoyancy forces in an opposite direction to the flow from diffusers. This layout can also be called vertical ventilation or diffuse ceiling inlet.

High ventilation effectiveness requires low location of supply openings in case of cooling, and it takes place when the flow is controlled by buoyancy forces. High ventilation effectiveness can also be obtained by a momentum driven plug flow, but the flow rate has to be very high in this case.

A number of experiments with different air distribution systems are shown, and they illustrate the behaviour at the different conditions discussed in the paper. Diffuse ceiling inlet and vertical ventilation with large supply openings, a_o/A , and radial ceiling-mounted diffusers are systems, which are able to handle a higher heat load than any of the other systems because they do not generate draught by the supply flow. The heat sources generate the draught in the occupied zone. They are all creating a ventilation effectiveness of ~ 1.0 .

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