ASSEMBLY HALL AIR DISTRIBUTION

Introduction:

H.V.A.C. system design for assembly halls demands that specific attention be paid to the provision of enhanced comfort and low levels of noise, due to the greater thermal sensitivity of the typically sedentary occupants and the extremely high acoustical requirements of such spaces. However, equal distribution of thermal comfort, draught-free air motion and efficient fresh air supply are difficult to achieve in these – typically high-stud – applications. The reasons for these difficulties are outlined below together with a discussion of available solutions in which strengths and weaknesses of each possibility are highlighted.

High-level Air Distribution Systems:

Thermal comfort is not easy to achieve for people who are seated and inactive for prolonged periods of time, as their bodies do not require much heat removal and are prone to feeling draughts, and as such occupants are least able to alter position or clothing to overcome discomfort. Halls filled with people typically require cooling (even in winter) to remove the tremendous heat-load produced by the high concentration of people. However, the supply of cold air carries with it the greatest risk of producing sensations of draught. To combat this, air is traditionally supplied at a high level, so that both mixing of cold supply air with warm room air and high air velocities produced by supply air streams are restricted to the zone above the occupied space. Even so, dumping of cold bundles of dense supply air typically occurs, especially where long throws are involved, causing draughts *(fig. 1)*.

– Tangential Airflow: Cooling
- Poor mixing
- Poor temperature equalisation
- Dumping
- Draughts
- Ventilation effectiveness < 1

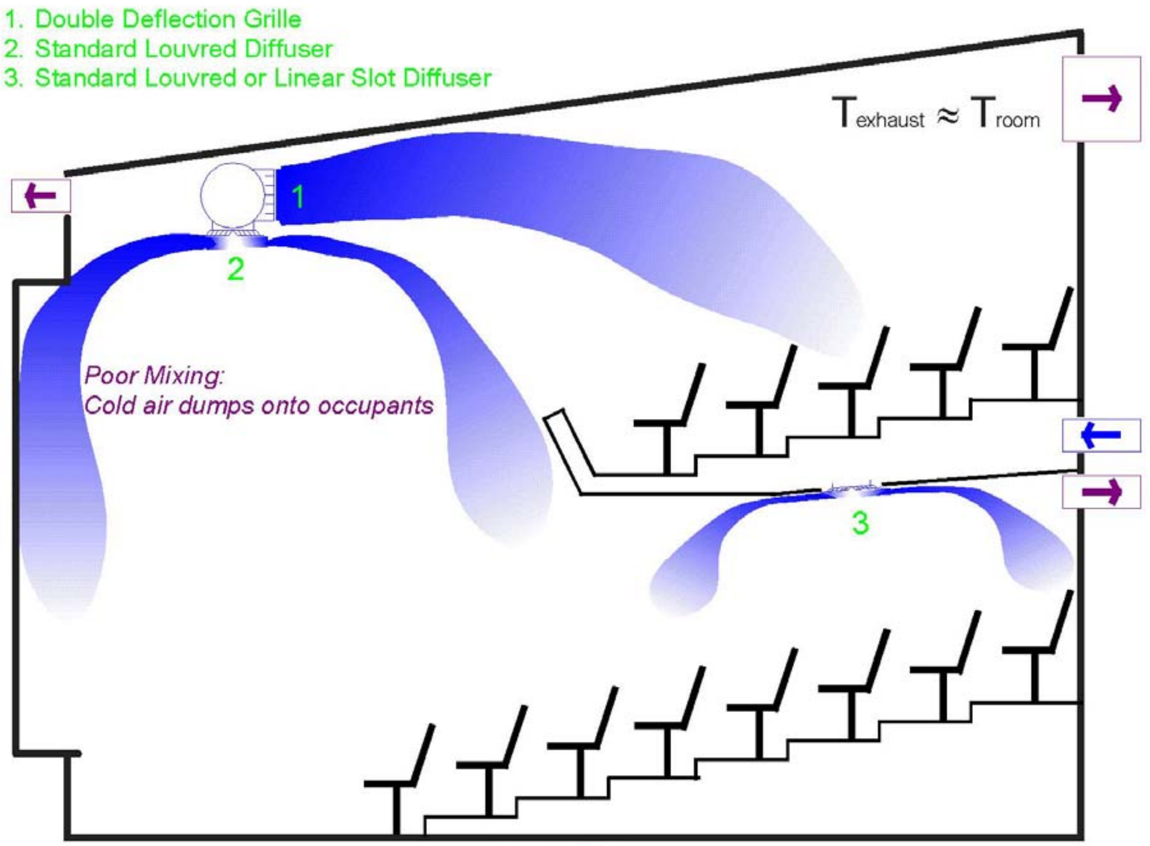


Fig.1 COOLING

As a partial remedy, and in order to lengthen throws, diffusers are often placed to blow along the ceiling, creating Coanda-effect suction of the air bundles to this surface. Such suction increases the area over which the cooling effect is spread before the bundles slow down, detach and dump. While localised dumping is reduced, it is not eliminated. Moreover, Coanda-effect attachment requires high velocity discharge to create suction to the ceiling – such high velocity, in itself, can cause draughts, especially down walls or where two cold air bundles collide. Additionally, the sound power level of the diffusers increases.

Winter heating, which is necessary to pre-condition the space and during periods of low occupant density, is difficult to achieve if a high-level supply system is used. This is especially true if discharge and return air grilles are both located above the occupancy zone, as heat naturally wishes to short-circuit in the upper portion of the space *(fig. 2)*. Poor mixing and Coanda-effect ceiling suction exacerbate this problem, as both buoyancy of the hot supply air bundles and ceiling suction of these bundles' air streams prevent supplied warmth from penetrating down to the occupants. By relocating extraction to a low level to scavenge heavy, cold air from the floor, heating efficiency is improved, as this draws down buoyant warmth to lower levels. Despite this, efficiency is traditionally poor, as the coldest air stratifies to a low level to envelop the occupants, while the hottest air wastefully accumulates beneath the roof. Moreover, this inefficient penetration of heat to a low level causes occupants to raise heating set-point excessively, prolonging heater operation and raising supply air temperature – and hence bundle buoyancy. Consequently, the warm supply air becomes even lighter and even more difficult to bring down, and warming up sequences required to fill the high level reservoir with heat increase, adding to inefficiency and adversely impacting on both power consumption and equipment wear-and-tear.

– Tangential Airflow: Heating
- Poor mixing
- Poor temperature equalisation
- Short circuiting
- Stagnation
- Ventilation effectiveness < < 1

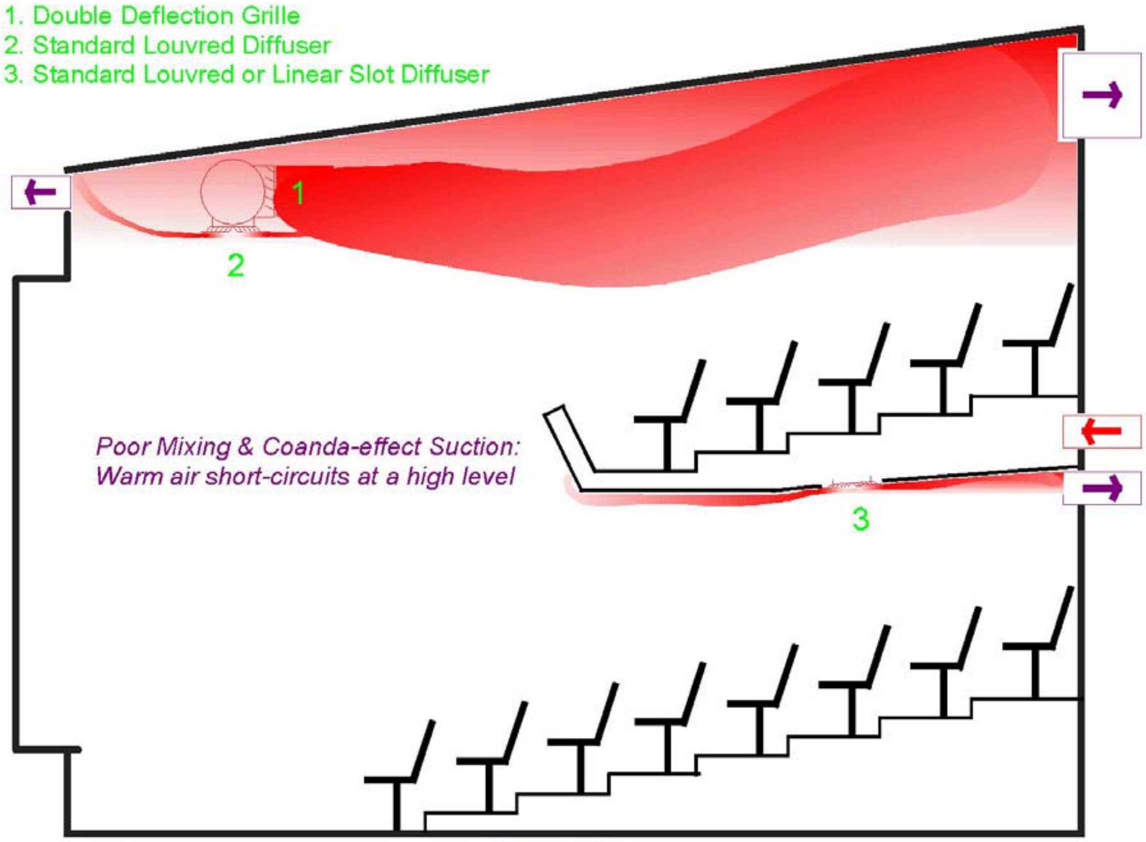


Fig.2 HEATING

– Nozzles: Cooling

- Quiet operation
- Greater mixing improves temperature equalisation & reduces trajectory fluctuation
- High comfort
- Ventilation effectiveness ≈ 1
- 4.5 m ≤ Throw ≤ 30 m
- 2.3 m ≤ $H_{DISCHARGE}$ ≤ 10 m
- Angle nozzles 10° to 15° upwards
- Separation distance ≥ 3 x Discharge diameter
- Volume flow rate ≤ 140 L/(s·m)
- $\Delta T_{SUPPLY\text{-}ROOM}$ ≤ -8 K

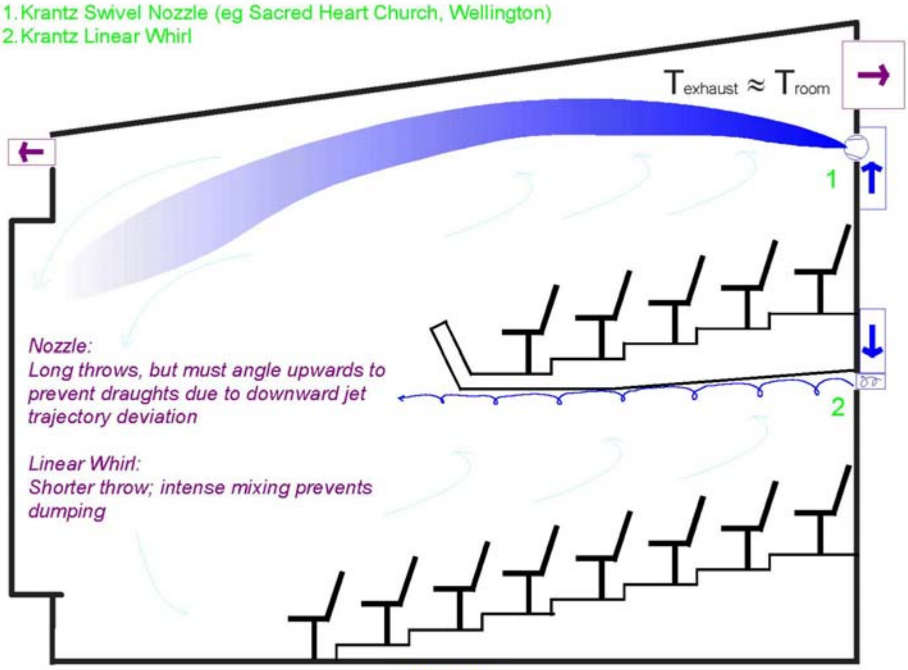


Fig.3 COOLING

– Nozzles: Heating

- Quiet operation
- Improved mixing
- Improved temperature equalisation
- Improved comfort
- Ventilation effectiveness < 1
- 2.3 m ≤ $H_{DISCHARGE}$ ≤ 10 m
- $\Delta T_{SUPPLY\text{-}ROOM}$ ≤ +5 K (dependent on discharge height)
- 30% to 50% Low level extraction re for +5 K ≤ $\Delta T_{SUPPLY\text{-}ROOM}$ ≤ +10 K

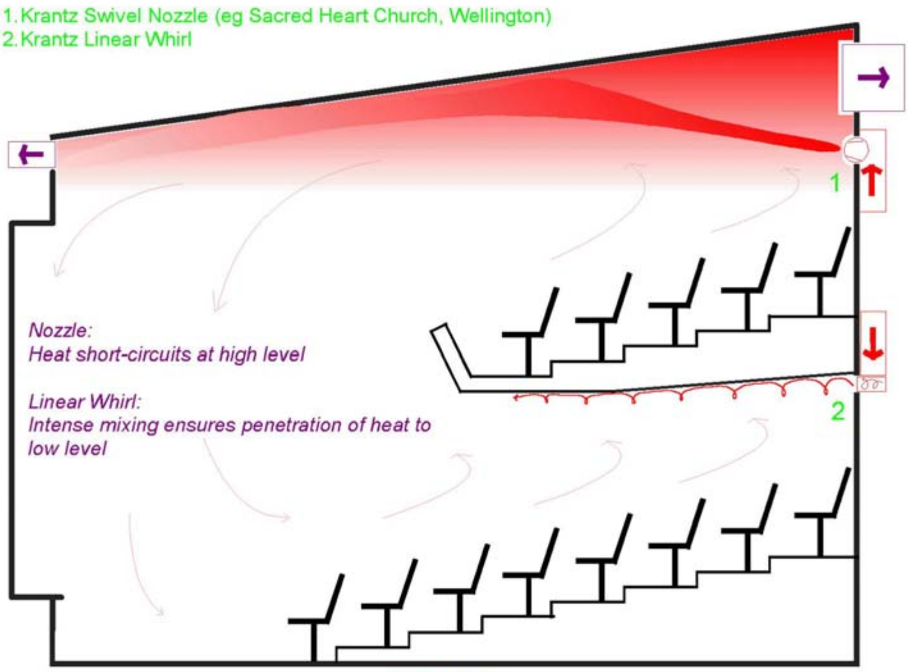


Fig.4 HEATING

Rather than blowing unsteady masses of air into open spaces, or sucking such unstable bundles to ceilings by means of Coanda-effect attachment, high velocity nozzles can be used to concentrate supply air into narrow jets that are shot across high level open spaces. The high momentum of each jet stabilises and extends the cold or warm supply streams' otherwise limp trajectories, eliminating icy dumping onto unsuspecting occupants or plumes of supplied heat from ineffectively wafting upwards to the roof. Moreover, high velocities, narrow streams and long throws increase entrainment of room air into each jet, diluting jet temperature differential and air density to reduce trajectory deviation as jet velocity drops towards the end of its throw *(fig. 3)*. The absence of guide elements within the nozzles brings a further advantage – quiet operation – allowing unusually high discharge velocities to be used to achieve the above effects and increase throw. In order to prevent draughts, nozzles should always be directed slightly upwards; while this compromises heating performance *(fig. 4)*, nozzles still outperform grilles blowing into open spaces or along ceiling surfaces. High velocity nozzles, therefore, are ideal for spaces requiring draught-free cooling, long throws and silent operation.

Weser-Ems Multipurpose Hall, Oldenburg, Germany

From the above it is evident that if high velocity air streams could be made even narrower and highly turbulent, then even greater diffuser thermal performance would be realised. The reason for this is that induction of room air directly at each diffuser would be increased, realising thorough room air mixing with the individual supply air streams, intensely diluting the temperature differential and air density directly at the diffuser (to reduce trajectory deviation over throw) and rapidly breaking down discharge velocity (to bring about gentle, evenly spread and draught-free air motion in the whole room). Twist outlets do precisely this *(fig. 5)*: A multitude of high velocity, narrow and extremely turbulent free-streams is discharged; intense mixing quickly equalises supply air temperature and density with that in the room; free-stream velocity is broken down rapidly; resultant low velocity air motion is completely stable, gently and evenly distributing temperature both horizontally and vertically within the occupied space. Additional advantages are that large volume rates of air can be discharged from each diffuser without disturbing free-stream stability; diffusers can be freely suspended in the space since Coanda ceiling suction is not required; greater heating and cooling temperature differentials between supply and room air are sustainable bringing about reductions in requisite volume flow rates to cover heat loads; and extremely high levels of comfort and efficiency can be achieved in both cooling and heating modes, largely irrespective of discharge height.

Of course, limitations do exist to the thermal loads that can be covered, and to the discharge heights that can be used: ultimately, the laws of physics will prevail. Where internal loads fluctuate significantly or both cooling and heating are required from extreme discharge heights, twist outlets with adjustable discharge direction should be used to further improve performance by directing cold supply air horizontally and warm supply air downwards to counteract changing density *(fig. 6)*. The density is that of the supply air relative to the room air; for this reason, discharge direction control should always be based on the temperature difference between supply air and room air, and not only on the temperature of the supply air. As an example, to effectively warm up a 16°C room using 20°C supply air, downward projection is required; for draught-free cooling of a 21°C room by means of 20°C supply air, horizontal projection is required. It is also important to have continuously variable throw adjustment, so that under- or over-throw are averted as internal loads fluctuate. Discharge direction is altered by either swivelling – upwards and downwards –

– Diffuse: Cooling
- Rapid temperature equalisation & velocity break-down due to intense mixing
- Stable discharge pattern - no Coanda required
- Modulating discharge direction
- Even temperature distribution
- Draught-free comfort
- Ventilation effectiveness ≈ 1
- $2.2\ m \leq H_{DISCHARGE} \leq 20\ m$
- Volume flow rate ≤ 2800 L/s
- $\Delta T_{SUPPLY\text{-}ROOM} \leq -12\ K$

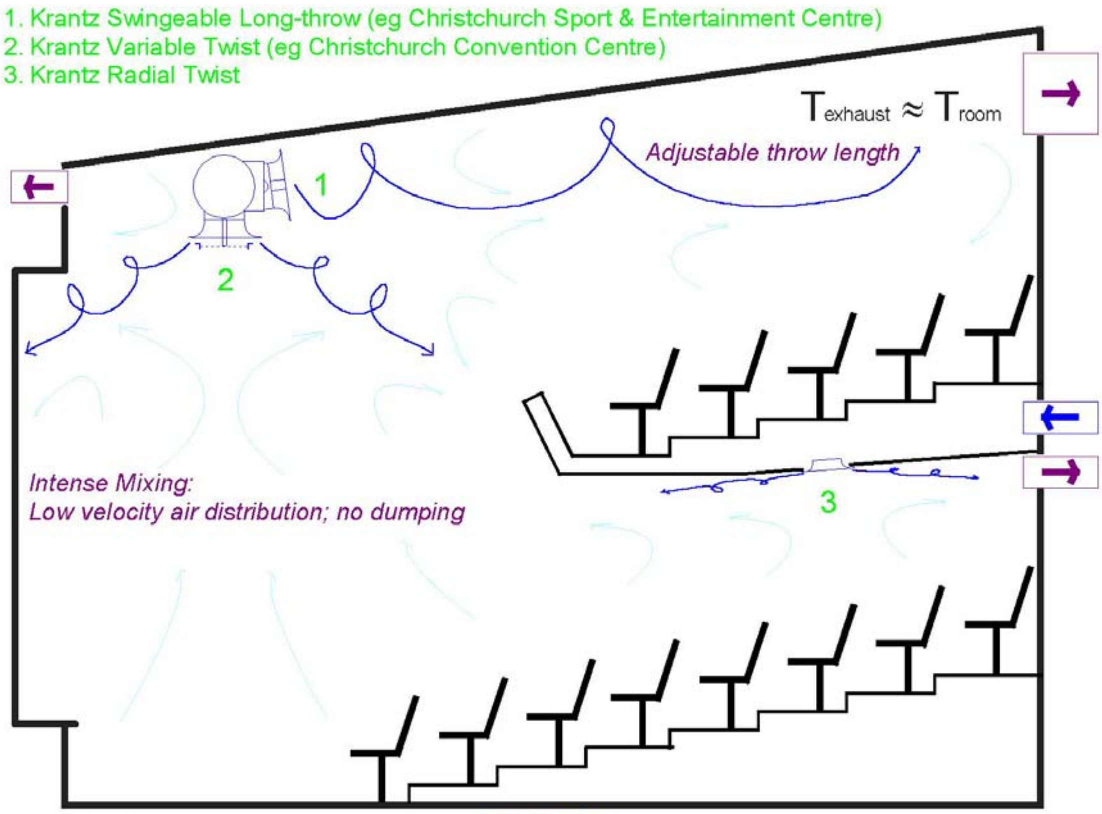


Fig.5 COOLING

sideways throwing twist outlets (whose horizontal throw distance is additionally manually adjusted) or by altering the discharge pattern of roof-mounted twist outlets from a horizontal disk-shape to a variable downward cone. Such adjustable discharge direction is extremely effective in achieving draught-free cooling and in ensuring that heat is effectively pushed down to the occupants when this is required. Not only are comfort levels improved but winter warm-up times are also shortened, and operating costs in terms of power bills and equipment wear-and-tear are dramatically reduced. The advantages of highly turbulent discharge, however, come at a price – the all-important internal guide elements that create the requisite intense turbulence also create noise. While these diffusers can realise extremely effective heating from discharge heights of up to 25 m, the

Christchurch Convention Centre

Westpac Centre, New Zealand

required discharge velocities increase with increasing height and hence impact negatively on acoustical performance. The Christchurch Convention Centre is an example of heating and cooling air distribution from a high level using adjustable twist outlets whose automatic discharge direction control works as a function of the supply-to-room temperature differential. Exhaust air is extracted from above the diffusers which discharge from 8 m height; this moderate discharge height made it possible to realise

– Diffuse: Heating
- Rapid temperature equalisation & velocity break-down due to intense mixing
- Modulating discharge direction
- Draught-free comfort
- Ventilation effectiveness ≈ 1
- $\Delta T_{SUPPLY\text{-}ROOM} \leq +12$ K (dependent on $H_{DISCHARGE}$)
- $2.2 \text{ m} \leq H_{DISCHARGE} \leq 20 \text{ m}$
- 30% to 50% Low level extraction when $\Delta T_{SUPPLY\text{-}ROOM} > \Delta T_{DIFFUSER\ MAX.\ PERMISSIBLE\ SUP\text{-}ROOM}$
- Rapid warm-up - Increase diffuser flow rate by shutting off airflow to some diffusers

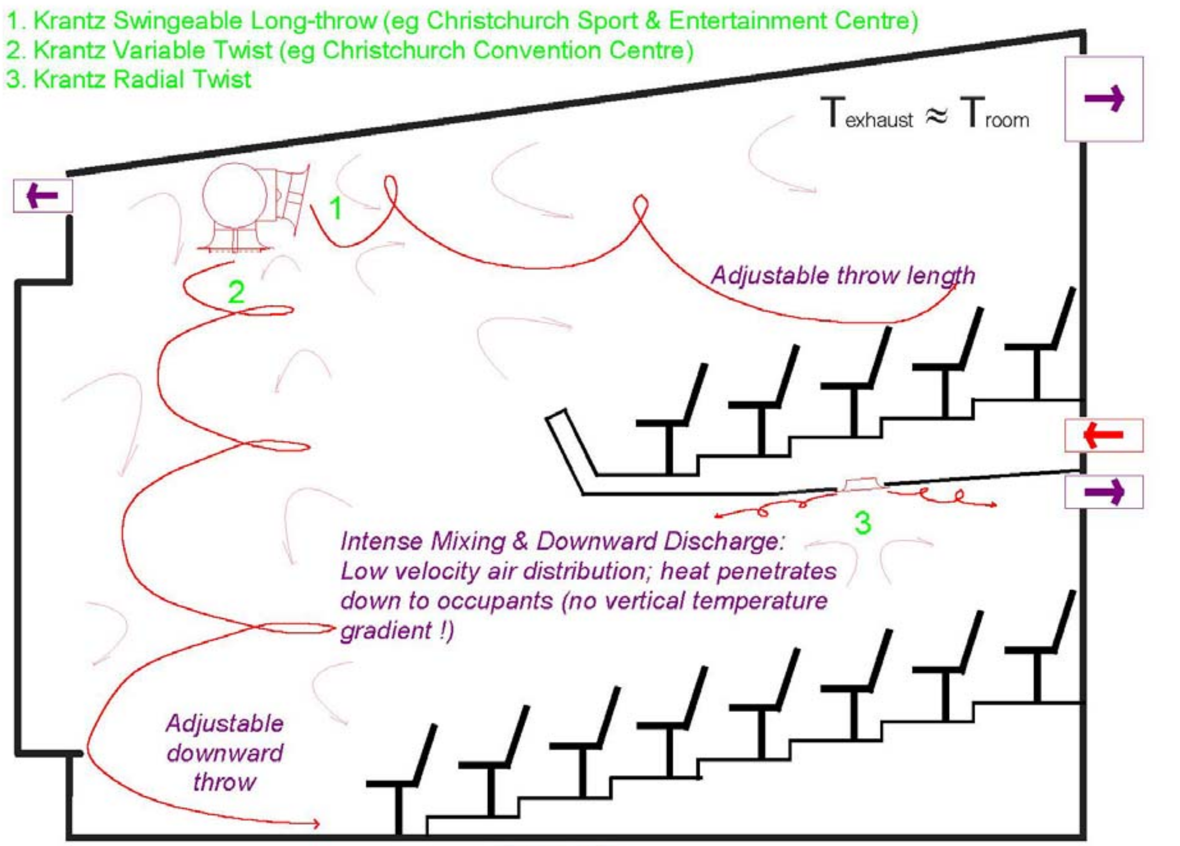


Fig.6 HEATING

Academisch Centrum, Tandullkunde, Amsterdam, NL

Albert-Schultz-Eishalle, Vienna, Austria extremely quiet operation of less than PNC30. In contrast, similar 16 m high air distribution at the Christchurch Sport & Entertainment Centre has a noise level of about PNC35 due to the higher discharge velocities required for effective heating; additionally, 50% of the return air is drawn from a low level to aide heating performance.

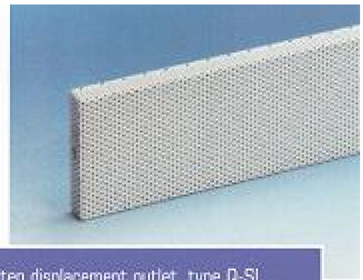
The high-level discharge systems described above distribute fresh air to occupants by mixing and diluting supply air with the air in the entire space. In maximum cooling mode, supply air is typically discharged at 12 to 14°C, with exhaust temperature approximating room temperature (approx. 22°C), realising a supply-to-exhaust temperature differential of about 9 K. It can be argued, however, that volume flow rates could be reduced by increasing this temperature differential, and that capacity, fresh air and energy could be saved if conditioning were restricted to only the low-lying occupancy zone rather than being wasted on the entire hall volume? An entirely different approach to air distribution is thus possible to address this potential for improved performance. This approach is presented in the following section.

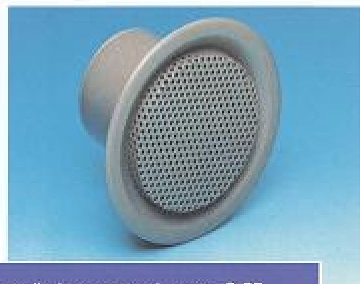
Low-level Air Distribution Systems:

Low-level air distribution systems combined with high-level extraction are designed to improve levels of comfort and air freshness and to reduce system capacity requirements by restricting conditioned air to the occupied space, by allowing heat and pollutants emanating from this space to separate into a hot, high-level blanket of contaminants, and by exhausting this concentration of heat and contaminants to the outdoors. While high-level discharge systems fight against plumes of heat and pollutants rising naturally from occupants, mixing these back down to the occupied space, low-level discharge systems complement the gentle upward flow of these natural thermals and their entrained contaminants to ensure their effective removal from the occupants. This is done by means of a slow, supporting, upward airflow that aides in concentrating contaminant accumulation into layers of stratification beneath the ceiling, whilst simultaneously replenishing the occupied space with conditioned and undiluted freshness. This can, however, only be achieved if occupants do not disturb the airflow; in other words, they should be largely seated and remain so for prolonged periods of time. Benefits in terms of system design and efficiency are pronounced: In high ceiling applications the high level


Theatre Hof, Berlin, Germany


Seat displacement outlet, type Q-St


Step displacement outlet, type Q-SL


Step displacement outlet, type Q-SR

temperatures rise to as much as 30°C, thereby allowing supply temperatures as high as 18 to 20°C to be used whilst simultaneously increasing the supply-to-exhaust temperature differential from the above mentioned 9 K (for high-level mixed flow) to about 11 K. As a result, the amount of airflow required for heat removal can be reduced by about 20%! Moreover, as unusually high supply air temperatures are employed to achieve cooling, free-cooling using only outdoor air can be more effectively utilised (up to outdoor temperatures of 18 to 20°C rather than a mere 12 to 14°C) and systems can be designed to run on 100% outdoor air. This reduces both the capacity of mechanical cooling equipment required and associated mechanical cooling running time. Capital cost reductions and energy savings are significant, and occupant comfort and health levels are enhanced.

Since air is to be distributed directly at the occupants and is not to induce high level heat, care must be taken as to the manner in which the air is discharged into the space. Unless carefully designed, low-level air distribution systems will create discomfort, especially as cool supply air falls naturally and as ankles are unusually sensitive to draughts. Double deflection grilles and linear slots are not suitable, as their discharge velocities under stable operation are too high. Instead, use should be made of displacement air outlets in walls, steps or seat pedestals, or of small, highly inductive diffusers in the floor or steps, or integrated into seats.

Displacement outlets *(fig. 7)* allow supply air at 19 to 20°C to ooze out with minimal turbulence, over large perforated surfaces, and at an extremely low velocity of less than 0.2 m/s, with typical discharge rates being 10 to 12 L/s per person. Consequently, draught sensation is avoided by creating a non-turbulent, low velocity (< 0.17 m/s), ankle-high "lake" of heavy air that spreads around, flooding the floor. While the air temperature of this "lake" is no lower than 21°C, it is

– Displacement - Step & Pedestal: Cooling

- Exhaust from a high level
- Return air (if any) from a low level
- Seating: undefined (step); fixed (pedestal)
- Ventilation effectiveness ≈2.0
- Flow rate: 8 to 12 L/(s•person)
- T_{SUPPLY}: ≥19°C (step); ≥20°C (pedestal)
- T_{ANKLE} ≥21°C
- T_{FACE} ≈23°C
- $T_{EXHAUST}$ ≤30°C
- $\Delta T_{FACE-ANKLE}$ ≤2.0 K/m
- $V_{ANKLE/FACE}$: 0.16/<0.1 m/s

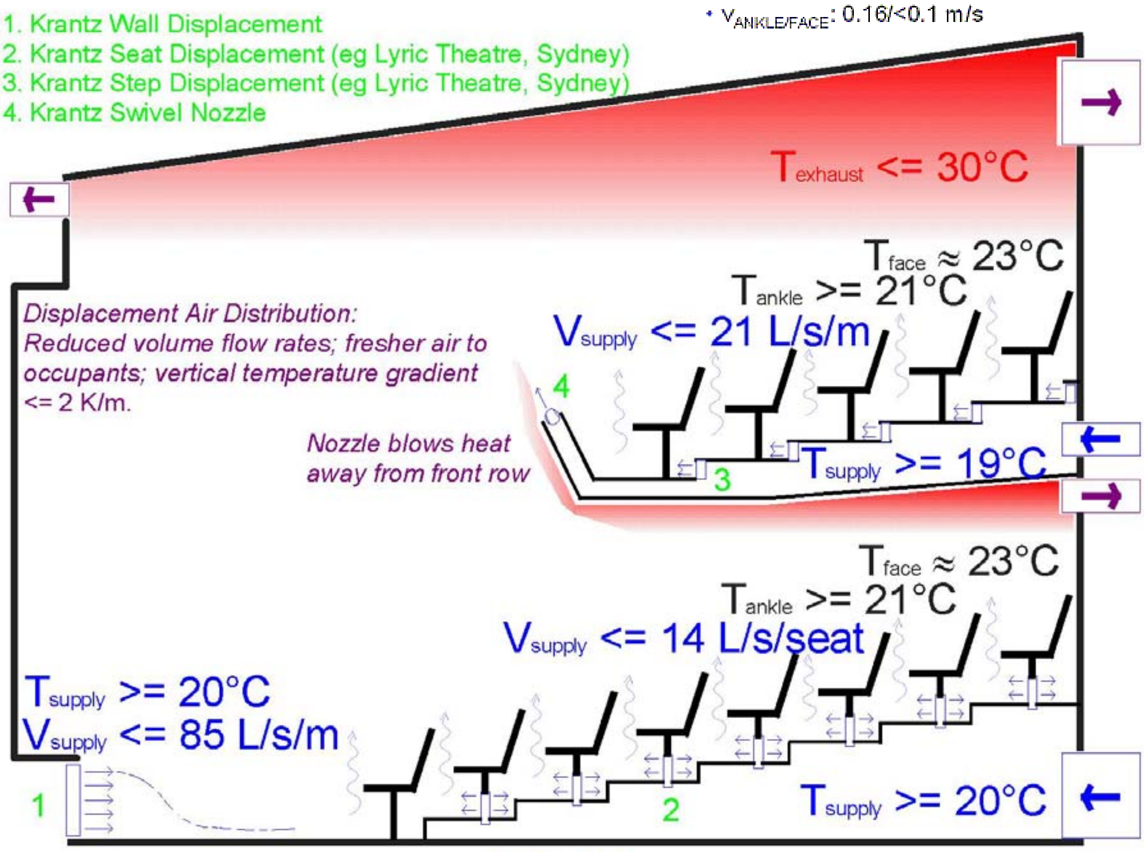


Fig.7

slightly cooler than the air above it. For this reason and due to the lack of turbulence, the two air masses do not mix. Instead, fresh air from this "lake" is drawn up naturally by thermals rising around heat sources – people are thus enveloped in the cool freshness that replenishes the warm, polluted plumes of convection rising above their heads. Facial temperatures of 23°C are typical since the ankle-to-facial vertical temperature gradient is about 2 K; the high exhaust temperature of up to 30°C does not compromise thermal comfort.

– Twist & Micro-climate: Cooling

- Exhaust from a high level
- Return air (if any) from a low level
- Seating: undefined (twist); fixed (micro-climate)
- Flow rate: 8 to 12 L/(s•person)
- T_{SUPPLY} ≥18°C
- T_{ANKLE} ≥21°C
- T_{FACE}: ≈22.5°C (twist); ≈23.5°C (micro)
- $T_{EXHAUST}$ ≤30°C
- $\Delta T_{FACE-ANKLE}$ ≤1.5K/m (twist); ≤1.0K/m (micro)
- $V_{ANKLE/FACE}$: 0.13/<0.1(twist); 0.13/0.17m/s(micro)
- Ventilation effectiveness ≈1.5

Improvements in system efficiency can be realised if the temperature difference between supply and return air can be further increased, thereby further reducing volume flow rate requirements. Since ceiling temperatures greater than 30°C noticeably radiate heat, and hence cause discomfort, such an increase in the temperature differential can only be achieved by reducing supply air temperature. A supply air temperature reduction cannot be achieved with displacement systems without

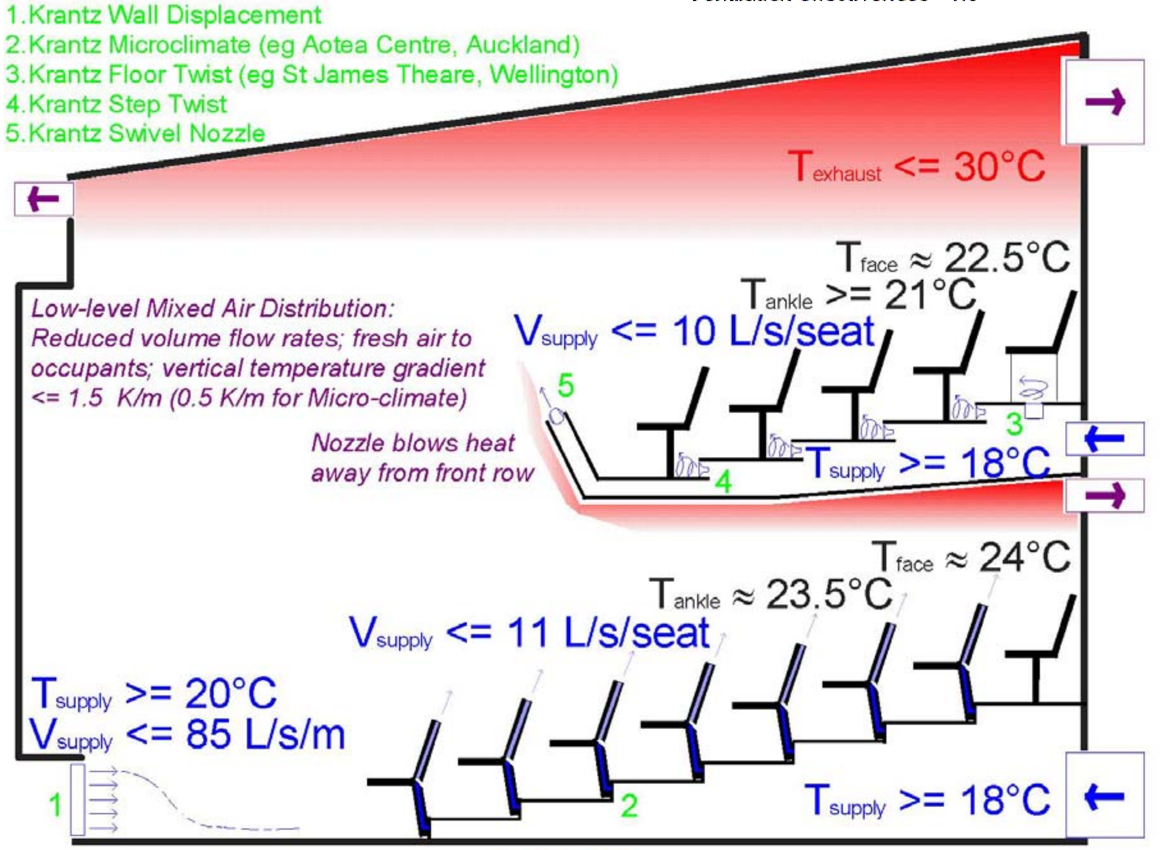
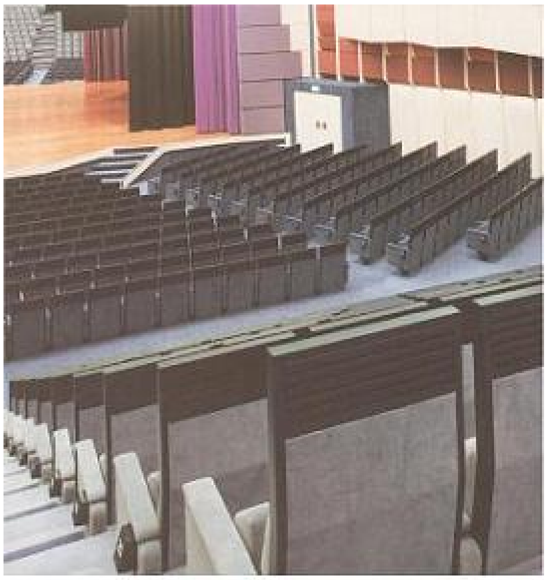


Fig.8 COOLING

creating low-level draughts. It can, however, be achieved if a mixed flow discharge system is used to subsequently raise the supply air temperature by means of dilution with slightly warmer air from the occupied space. Supply air temperature can be dropped to 18°C (increasing the supply-to-exhaust temperature differential to 12 K and hence allowing airflow to be reduced to 3/4 of what would be required using a high-level mixed flow system) if highly turbulent discharge through small twist outlets (floor or step mounted) is used beneath each seat *(fig. 8).* Discharge is typically at a rate of 10 L/s per person, and dilution of supply air with induced warmer room air ensures that ankle temperature does not drop below 21°C. High induction favourably reduces the occupancy vertical temperature gradient to about 1.5 K and ensures that the air velocity around ankles is less than 0.14 m/s.

Max-Schmeling Hall, Berlin, Germany

Floor twist outlet, type DB-E in "De Koninklijke Schouwburg", The Hague (NL)



MECC Maastricht-Exposite & Congres Centrum, Maastricht, Netherlands

If the above concept could be further developed, then one would ideally say that a low-level discharge system is required that allows high-level contaminants to stratify and be exhausted at 30°C, that allows supply air temperatures as low as 18°C, and that raises comfort levels by providing a uniform temperature distribution in the occupied space to eliminate strong vertical temperature gradients around people. This system would maximise both efficiency and comfort; and this system exists – it is called the "micro-climate" induction system. In this system, rather than diluting supply air with room air at floor level, induction takes place within each seat backrest so that a mixture of supply air and occupancy zone air is discharged at about head height of each seated person. This allows 18°C supply air to be used whilst eliminating the threat of ankle level draughts for extremely sensitive people and reducing the ankle-to-facial vertical temperature gradient to an especially comfortable 0.5 K *(fig. 8).* This is the most sophisticated, comfortable and efficient air distribution system available for assembly halls, but it is limited in application due to both price and lack of functional flexibility for multipurpose halls. The Aotea Centre in Auckland is an example of this system, as is the Maastricht Exposite & Congres Centrum in the Netherlands.

Heating performance for the above mentioned low-level air distribution systems varies: wall displacement outlets are the least efficient, as warm supply air simply rises as plumes to short-circuit at a high level without purging the space; step and pedestal displacement systems perform somewhat better due to their even and concentrated distribution throughout the space; twist outlets and micro-climate systems provide effective heating due their strong low-level mixing of supply and room air.

Acoustical performance for each of the above low-level air distribution systems is good, due to the very low discharge velocities used.

Conclusions:

Low-level supply systems realise extremely high levels of comfort for applications involving high concentrations of people; low noise levels, high air quality in the occupancy zone, and low running costs (e.g. increased free-cooling, lower air volume rates, lower pressure drop, lower chiller costs) are further benefits of such systems. Low-level supply systems are, therefore, the preferred choice for assembly halls – on condition that the halls are to be used mainly for seated occupants. Of the available choices, micro-climate induction offers both the highest levels of comfort and efficiency, but realises little functional flexibility. Where the selection of low-level air distribution is not feasible, high-level discharge systems using adjustable twist outlets or nozzles should be applied: the former provide not only good cooling performance but also effective heating as well as automatic adjustment to fluctuations in thermal load; the latter's strengths are acoustical refinement and long horizontal throws. Traditional Coanda-effect airflow or grilles blowing into open spaces should not be used in assembly halls due to the extremely low levels of comfort and compromised efficiency that they produce.

Conclusions - High Level Discharge

– Advantages
- Tangential: cheap
- Nozzles: long throws; quiet
- Diffuse: heating; varying thermal loads; inexpensive

– Disadvantages
- Tangential: poor heating; low comfort
- Nozzles: poor heating; high cost
- Diffuse: noise

Conclusions - Low Level Discharge

– Advantages
- General: economical operation; high air quality
- Displacement: high comfort; aesthetics
- Twist: good heating; inexpensive
- Micro-climate: extremely high comfort

– Disadvantages
- Displacement: poor heating; expensive
- Twist: comfort not as high
- Micro-climate: extremely expensive

Written by Dr.-Ing. F. Sodec and Mr. Andre Göbel of Krantz Komponenten (Germany), and Sean Badenhorst of T.E.M.P.E.S.T. Ltd. (New Zealand) for the Journal of the Institute of Refrigeration, Heating & Air Conditioning Engineers, Volume 10, Number 5, 1998.

IRHACE Journal is the official journal of the Institue of Refrigeration, Heating and Air-Conditioning Engineers of New Zealand.