Improvements in natural air supply concerning thermal winter comfort, IAQ and energy consumption

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SUMMARY

The paper presents the effect on thermal conditions, heat consumption and the perception of thermal comfort and indoor air quality (IAQ) of different types of trickle ventilators (pressure controlled at 2 Pa pressure difference or 10 Pa with(out) back draft valve and with(out) demand controlled mechanical extract in all rooms), since these are key factors in the evaluation of the ventilators. All of these aspects are investigated by means of simulations (CFD parametric analysis and Contam) and measurements in a climatic chamber (cold box - hot box) in order to develop a trickle ventilator with improved performance.

PRACTICAL IMPLICATIONS

By means of simulations and full-scale measurements, input on how to design a trickle ventilator is gathered. Evaluation parameters are thermal comfort (draught rate (DR)), ventilation heat loss and IAQ (heating season integrated exposure to CO_2 > 600 ppm over outdoor concentration).

KEYWORDS

CFD parametric analysis, Contam, climatic chamber, draught rate

1 INTRODUCTION

Trickle ventilators (or vents) are commonly used means for air supply in natural ventilation, especially in Europe. These manually operated air inlets are fitted around window frames (preferably on the top) to allow outside air passing through. State of the art are pressure-controlled vents intended to provide a constant supply of air flow independent of wind- and temperature-induced pressures and humidity-controlled ventilators which regulates the air flow as a function of outdoor and indoor relative humidity (Karava, et al., 2003).

Many building standards dealing with trickle ventilators, precise a different pressure difference at which the nominal air flow capacity of the trickle ventilator is determined. Apart from the required air flow capacity, additional requirements such as low energy use, good thermal comfort, high indoor air quality and acoustic comfort have to be fulfilled before a ventilation system is deemed to perform adequately.

The most commonly used equation describing the air flow Q (m^3/s) through an opening is the orifice equation

$$Q = C_D \cdot A \cdot \left(\frac{2\Delta P}{\rho}\right)^n \tag{1}$$

where C_D is the discharge coefficient of the opening depending on its geometry, n the flow exponent depending on the Reynolds number of the flow [0.5 – 1], A is the cross section of the opening (m²), ΔP is the pressure difference across the opening (Pa) and ρ is the air density (kg/m³). The discharge coefficient C_D is a dimensionless number that takes into account the influence of contraction and friction.

The aim of this paper is to present the results of both simulations and full-scale experimental investigations of different control mechanisms (pressure controlled at 2 Pa pressure difference or 10 Pa with(out) back draft valve and with(out) mechanical extract in all rooms) in order to develop a ventilator with improved performance independent of outdoor conditions.

2 METHODS

Energy use and comfort (thermal comfort, indoor air quality and acoustics) are key factors in the evaluation of ventilators. Different methods were used to analyse one or more factors. Since acoustics is a very specific research topic, it is only briefly handled in this paper. Thermal comfort was analysed by a Computational Fluid Dynamics (CFD) parametric analysis and climatic chamber measurements. Contam simulations were performed in order to trade-off energy consumption and indoor air quality of different variants.

CFD parametric analysis

The thermal comfort was evaluated in a rectangular room (2.500 x 5.000 x 3.000/10.000 mm [h x w x d]) in which an air inlet was located above the window, based on several varying input parameters that can be either geometrical or physical (Figure 1). By assessing the thermal comfort for a complete range of parameters, the set of parameters that can limit or avoid discomfort could be identified.

Since ten parameters were selected (Figure 1), a large number of CFD computations would be required in order to cover the whole range of possible configurations (for instance taking only two possible values per parameter would lead to 1024 computations). A popular way of handling such problems is applying approximation methods to produce a so-called surrogate model, which is a multidimensional mathematical representation of the outputs of the model, based on a limited subset of computations for which the input parameters have been intelligently chosen (Goethals, et al., 2012). The parametric analysis was driven by Cenaero's in-house optimization tool: MINAMO. CFD simulations to enrich the surrogate model were performed in Fluent.

The impact of each parameter on the global comfort in the room was evaluated by describing output parameters that will be processed in order to evaluate the comfort and classify the configurations. A common way of expressing comfort in a room is by the Draught Rate (DR), which expresses the percentage of people predicted to be bothered by draught (Anon., 2005) and calculated by the following expression:

$$\mathrm{DR}=\left(34-t_{a,l}\right)\left(\overline{v_{a,l}}-0{,}05\right)^{0{,}62}\left(0{,}37\cdot\overline{v_{a,l}}\cdot T_u+3{,}14\right) \tag{2}$$

with $v_{a,l}$ being the local mean air velocity (m/s), $t_{a,l}$ the local air temperature (°C) and T_u the local turbulence intensity. In order to have a relevant insight of the thermal comfort and the IAQ within the room, four output parameters were defined:

a) the Air Diffusion Performance Index (ADPI),

b) the global ΔDR (DR),
c) the surface ΔDR_S at the surface of 0,1 m height (DRS) and
d) the Mean Age of Air (MAOA) at 1,1 m height.

The first output parameter is the ADPI which is the ratio of the “comfortable” volume on the total volume of the room. “Total” volume must be understood as the “Life Volume”, which is the volume of the room in which the inhabitants are effectively likely to be present (1 m from a window, 0,5 m from a wall and 1,8 m height). The “comfortable” volume is described as the fraction of the “Life Volume” in which the DR is below a given threshold. This first indicator gives a global volumetric overview on the comfort level in the room, but does not give any precise idea of quantification of the discomfort, if any. For this reason, the notion of ΔDR is introduced to give more quantitative results. The idea is to evaluate the difference between the local DR and a threshold value. In order to correctly weigh the zones in which the difference will be noticed, it is important to take the volume of the local discomfort zone into account. Therefore ΔDR is expressed as:

$$\Delta DR = \sum_{i=0}^{ncells} \Delta DR_i \, V_i \div \sum_{i=0}^{ncells} V_i \qquad (3)$$

with ΔDR_i being the difference between the DR at a certain cell and a threshold value. With this global expression of ΔDR, each cell having a ΔDR above the threshold value is weighted by its cell volume, and the total is then divided by the discomfort volume. According to ISO 7730 DR threshold values are typical 10% (category A) to 20% (category B). In the simulations this threshold needed to be set much lower (3%) in order to have some discomfort zones and to be able to differentiate the results based on this indicator.

Another zone of interest is located at the ankles level (0,1 m height). The same approach as for the ΔDR is applied, but now only evaluated in a horizontal plane at 0,1 m height. This new output is called ΔDR_S. The last indicator, MAOA on the horizontal plane at a height of 1,1 m, is quite usual in the evaluation of IAQ and the air renewal rate.

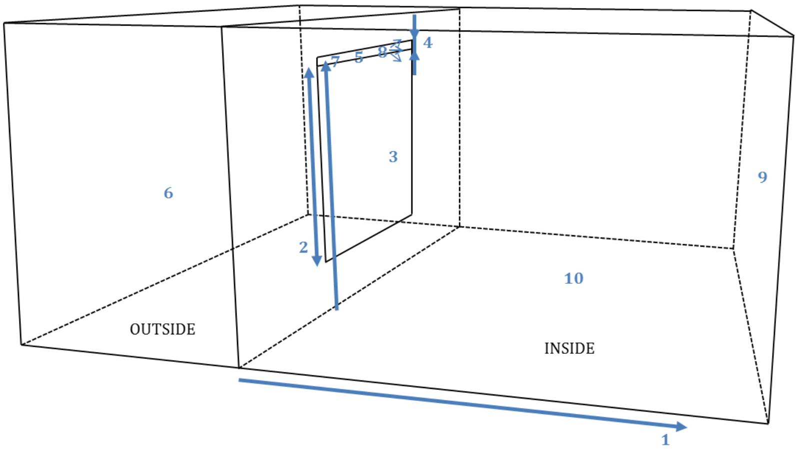


Figure 1. Varying parameters during CFD parametric analysis: room depth (1), frame height (2), U-value glass (3), height inlet opening (4), air flow rate (mass) (5), outside temperature (6), inlet to floor height (7), inlet angle (8), outlet location (9) and heating type (10).

Contam

Different ventilation system configurations were assessed through numerical simulations with the multi-zone airflow model Contam, developed by NIST. The calculation and evaluation process is described in (Savin & Laverge, 2011). For a building airtightness of $v_{50} = 0$ m³/h/m² (in order to see only the impact of ventilation) different system variants were traded-off according to IAQ (heating season integrated exposure to CO_2 > 600 ppm over outdoor concentration [ppm.h]) and ventilation energy consumption (heating season integrated ventilation heat loss [kWh/year]). The calculated variants were:

- VAR1: pressure controlled vents designed @ 2 Pa without back draft valve in dry rooms and with demand controlled extract in wet rooms (SOTA),
- VAR2: pressure controlled vents designed @ 2 Pa without back draft valve in dry rooms and with demand controlled extract in wet rooms **and sleeping rooms** (SOTA),
- VAR3: pressure controlled vents designed @ 2 Pa without back draft valve in dry rooms and with demand controlled extract in **all rooms**,
- VAR4: pressure controlled vents designed @ **10 Pa** without back draft valve in dry rooms and with demand controlled extract in **wet rooms**,
- VAR5: pressure controlled vents designed @ 10 Pa without back draft valve in dry rooms and with demand controlled extract in wet rooms **and sleeping rooms**,
- VAR6: pressure controlled vents designed @ 10 Pa without back draft valve in dry rooms and with demand controlled extract in **all rooms**,
- VAR7: pressure controlled vents designed @ 10 Pa **with back draft valve** in dry rooms and with demand controlled extract in all rooms.

Key aspect of this research is to determine whether it is possible to achieve good IAQ when the pressure difference at which the air flow capacity is determined, augments from 2 Pa to 10 Pa since this augmentation has a significant positive impact on energy loss (Figure 2) and acoustics. As can be deduced from equation (1): Q [m^3/h] ~ $\Delta p^{0.5}$ [Pa] and Q [m^3/h] ~ A [m^2]. Meaning that dimensioning the air flow rate at 10 Pa leads to a reduction of the opening by a factor ~ $\sqrt{10/2}$ ~ 2,2 which automatically leads to a better acoustical performance (+ 3 dB sound attenuation).

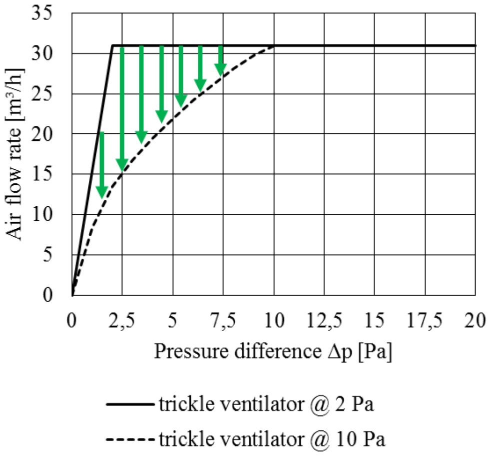


Figure 2. Reduced energy loss when dimensioning trickle ventilators at 10 Pa instead of 2 Pa pressure difference.

Figure 3. Hot box with prototype vent above the window and automatically moving measuring grid in the room.

Climatic chamber

The cold box - hot box at the Renson Research Center was used to compare with CFD results. To this end, the room dimensions in the CFD simulations were chosen similar. In the test setup the parameters having the largest impact according to CFD results together with the ventilation opening dimensioned by 10 Pa or 2 Pa were investigated with respect to thermal comfort. A measuring grid of 4 x 4 sensors in a vertical plane is present in the hot box which can be automatically displaced in the room (Figure 3). In this way, most of the space can be scanned to create 3D measuring maps of temperature, velocity and DR distribution in the room. The used measuring equipment was SENSOANEMO 5100SF, while analysis were performed with AirDistSys 5000 and own LabVIEW programming. Derived outputs were DR according to equation (2) and effective draft temperature (EDT)

$$EDT = (T_a(x) - T_a) - 8(v(x) - 0{,}15) \tag{4}$$

where $T_a(x)$ is the local airstream dry-bulb temperature (K), T_a the average (control) room dry-bulb temperature (K) and $v(x)$ the local airstream centreline velocity (m/s). The measuring grid is according to ISO 7726 meaning there are measuring points at 0,1 - 0,6 - 1,1 and 1,7 m height. The considered heating type was floor heating.

The global comfort of a tested case was assessed by using the same output parameters as defined for the CFD parametric analysis. ADPI was calculated for both effective draft temperature with threshold for comfort $-1{,}5\ \text{K} < EDT < 1\ \text{K}$ and $v < 0{,}35$ m/s (ASHRAE, 2009) and for DR. Both an evaluation in the "Life Volume" (LIV) similar to the CFD results and taking into account the whole space (ALL) were done. ΔDR was calculated with a threshold value of 15% (cf. ISO 7730) and of 3% (cf. CFD), both for the whole volume (V) as for the surface at 0,1 m height (S).

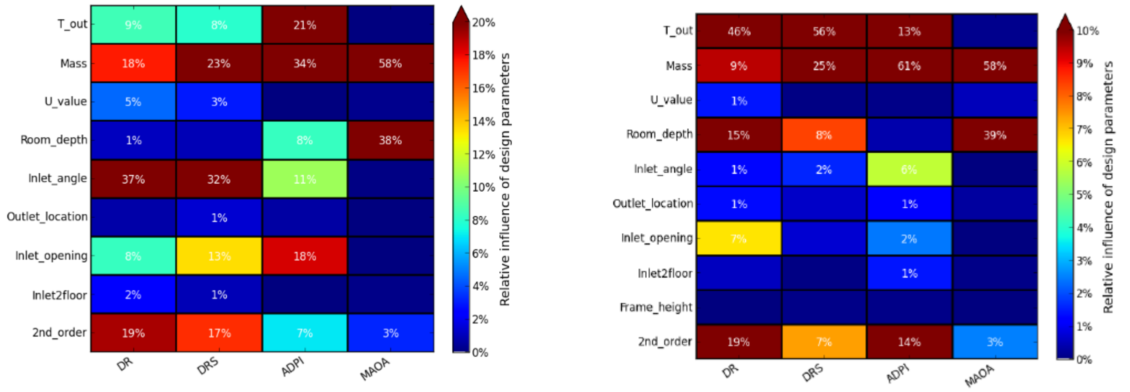
3 RESULTS

CFD parametric analysis

The summary of the parametric analysis is plotted on Figure 4. Each input parameter is marked according to their relative influence on the four output parameters. The outdoor temperature and air flow rate have clearly the largest impact on the output, definitely in the floor heating case. However, these factors cannot be changed by the design of the trickle vent. Designing a trickle ventilator which performs well no matter the outdoor climate or nominal air flow rate is the objective. Remarkably, second order effects (2nd_order) are reasonable but not negligible. Second order effects reflect the complexity of the problem since it can be seen as the impact of combined parameters on the results. For the floor heating case (which will be measured in the climatic chamber) the inlet angle and the height of the inlet opening have also a certain impact. Together with the air flow rate, the effect on ADPI is shown in more detail on Figure 5. The ADPI must be as high as possible (red zone on Figure 5).

a) In order to have high ADPI at every outdoor temperature, the air flow rate must be (logically) as low as possible. When achieving the nominal air flow rate at 10 Pa instead of 2 Pa pressure difference, the air flow rate is automatically reduced (cf. Figure 2) since pressure differences are usually varying from 0 to 20 Pa in Western Europe.
b) In order to have high ADPI at every air flow rate, the inlet angle is better negative (meaning the air flow is directed downward to the floor). Indeed, in the absence of a radiator, a positive inlet angle tends to project (cold) air directly into the "Life Volume", whereas a negative angle directs air firstly out of the defined "Life Volume". On the contrary, this kind of air flow is prevented in the presence of a radiator, acting as a "heat curtain".
c) In order to have high ADPI at every inlet angle, a higher inlet opening area (or lower design pressure difference) leads to a reduced air velocity. However, significant lower air flow rates at a higher design pressure difference (e.g. 10 Pa), neutralize this effect in practice.

Since outdoor temperature and air flow rate ("mass") are the dominating parameters, the influence of some other parameters can be shadowed. In fact parameters with very low influence can hardly be interpreted. A new approach, setting for instance a constant outdoor temperature could unveil the influence of the low influence parameters.



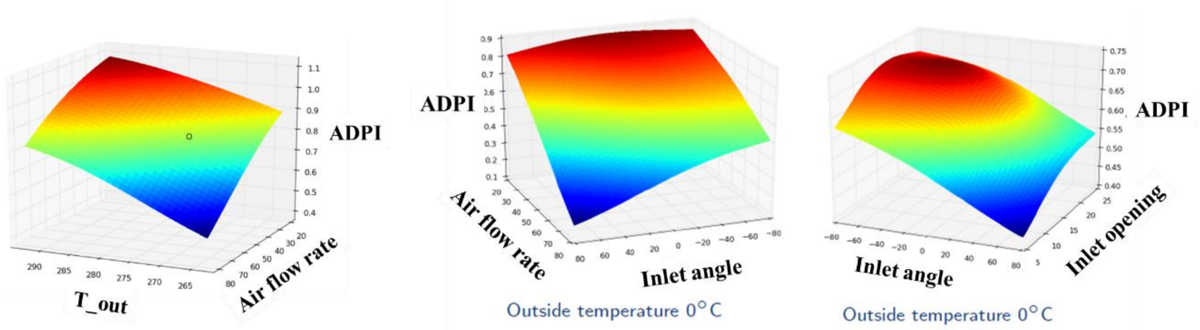
	DR	DRS	ADPI	MAOA
T_out	9%	8%	21%	
Mass	18%	23%	34%	58%
U_value	5%	3%		
Room_depth	1%		8%	38%
Inlet_angle	37%	32%	11%	
Outlet_location		1%		
Inlet_opening	8%	13%	18%	
Inlet2floor	2%	1%		
2nd_order	19%	17%	7%	3%

a) Radiator case.

	DR	DRS	ADPI	MAOA
T_out	46%	56%	13%	
Mass	9%	25%	61%	58%
U_value	1%			
Room_depth	15%	8%		39%
Inlet_angle	1%	2%	6%	
Outlet_location	1%		1%	
Inlet_opening	7%		2%	
Inlet2floor			1%	
Frame_height				
2nd_order	19%	7%	14%	3%

b) Floor heating case.

Figure 4. Result of parametric analysis. Relative influence of parameters on 4 outputs.



a) Influence of outdoor temperature [K] and air flow rate [m³/h].

b) Influence of air flow rate [m³/h] and inlet angle (<0 = downwards).

c) Influence of inlet angle and height of the inlet opening area [mm].

Figure 5. 3D plots floor heating case, on ADPI.

Contam

Results for the different variants are presented in Figure 6. Providing extra extract points in habitable rooms (VAR1 to VAR3 for 2 Pa and VAR4 to VAR 6 for 10 Pa) gives rise to better IAQ (-90%) but more heat loss (resp. +10% and +18%). Dimensioning the trickle ventilator at 10 Pa (VAR6 vs VAR3) has only a small negative impact on IAQ but reduces strongly the ventilation heat loss (-20%). When an asterisk (*) is added to the name of the variant in Figure 6, the reference building as described in (Savin & Laverge, 2011) was changed to one with an open kitchen, meaning no extra extract point is necessary in the living room and the nominal extract rate in the kitchen augments from 50 to 75 m³/h. The impact on heat loss (VAR6* vs VAR3*) is similar (-22%) as in the case with closed kitchen. Using a back draft valve in the vents (VAR7*) leads to an additional reduction of the heat loss (-10% to VAR6* and -30% to VAR3*) since cross ventilation is prevented and IAQ is still good.

Climatic chamber

The variation in height of the inlet opening area as simulated (Figure 5c) is validated for a specific case, namely the case of an inlet opening of 25 mm height which is reduced 2,5 times which represents the transition from an air flow rate dimensioned at 10 Pa to 2 Pa. Figure 7 shows the resulting DR plots (zones with highest DR are coloured red). The zones in which the highest differences occur between the two cases are highlighted on Figure 7. It can be concluded that in the 2 Pa case the air falls faster after the window than in the 10 Pa case. The definition of the “Life volume” with respect to the window is therefore a significant issue.

The variation in inlet angle as simulated (Figure 5b) is validated for a specific case, namely the 10 Pa case of Figure 7 with orientable valve (-45° downward; 0° horizontal; +45° upward). From Figure 8 can be deduced that a downward oriented inlet (-45°) performs similar as a horizontal inlet (0°) in contrast to an upward oriented inlet (45°) for which the air falls clearly later.

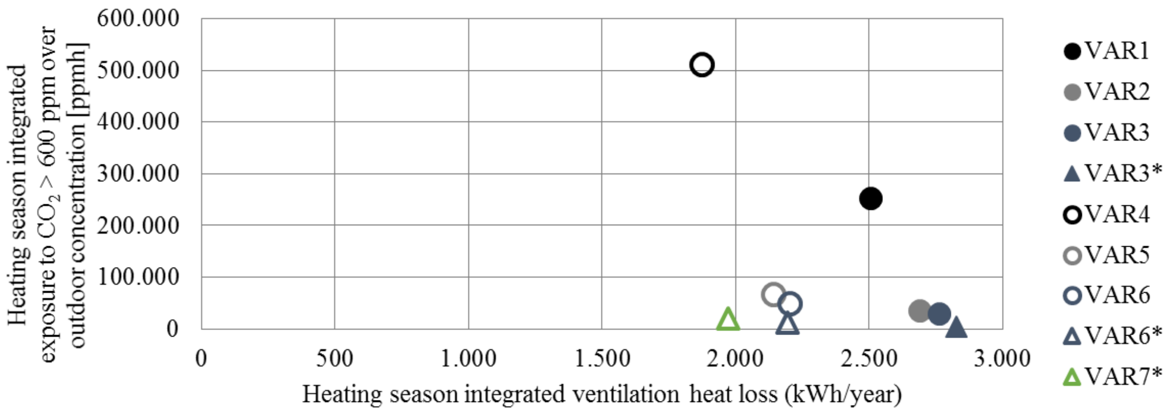


Figure 6. Trade-off of different ventilation principles according to energy use and IAQ.

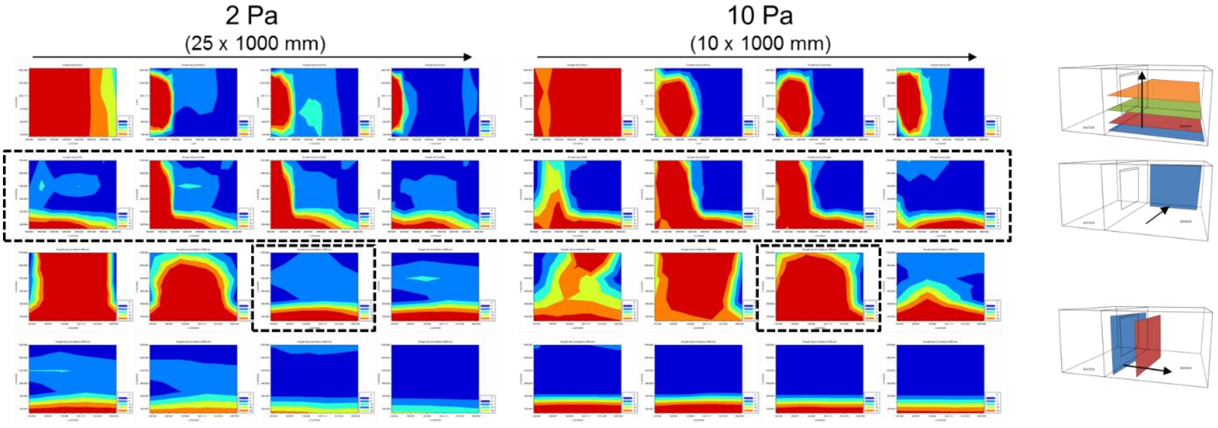


Figure 7. DR measurements in hot box (20°C) - cold box (0°C) @ 66 m³/h/m on trickle vents with varying height (equivalent to 2 Pa vs 10 Pa pressure difference) 0° inlet angle. First row from left to right: horizontal slices from bottom (0,1 m) to top (1,7 m). Second row from left to right: vertical slices perpendicular to window from left to right (0,5 m spacing). Third and fourth row from left to right: vertical slices parallel to window (0,5 m spacing).

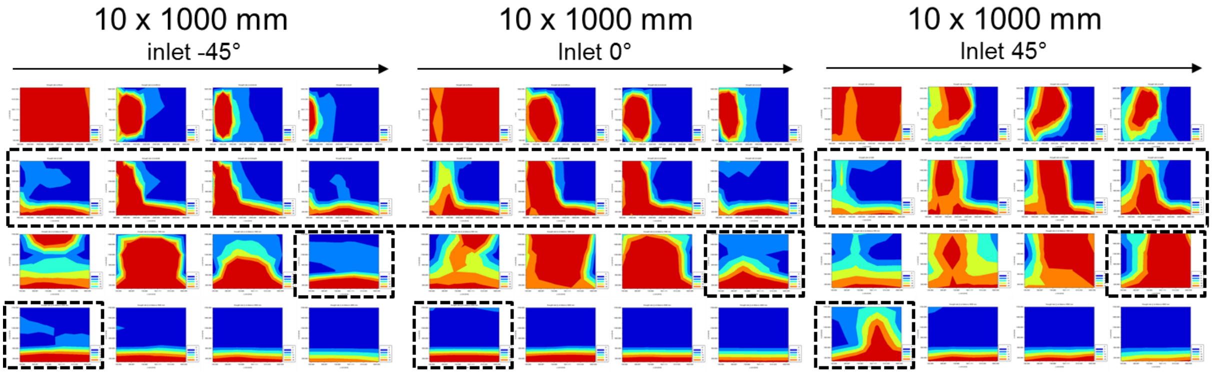


Figure 8. DR measurements in hot box (20°C) - cold box (0°C) @ 66 m³/h/m on trickle vents with varying inlet angle (-45°: downward and 45°: upward) 10 Pa.

In Table 1 the global comfort of the different cases is summarised. Overall only small differences are noticeable. The slightly worse output values of 10 Pa inlets, will in practice be compensated by lower mean air flow rates having a significant impact on thermal comfort. Furthermore, it is hard to draw conclusions especially since some contradictions occur. For instance regarding ADPI_EDT and ΔDR15 a 10 Pa upwards oriented inlet performs best, while regarding ADPI_DR15 this variant performs worst. Regarding ΔDR03 no real differences can be distinguished.

Table 1. Global comfort output parameters for climatic chamber measurements.

Parameter	2 Pa 0° inlet	10 Pa 0° inlet	10 Pa -45° inlet	10 Pa 45° inlet
ADPI_EDT_LIV	0,52	0,45	0,38	0,68
ADPI_DR15_LIV	0,76	0,62	0,70	0,55
ΔDR15_V	5,00	5,10	5,10	3,50
ΔDR15_S	10,00	11,20	12,70	7,10
ΔDR03_V	9,90	10,90	9,80	10,00
ΔDR03_S	21,60	23,30	24,70	19,10

4 CONCLUSIONS

When a higher design pressure difference of 10 Pa is applied for trickle vents combined with a mechanical extract point in the habitable room, a significant better IAQ and lower ventilation heat loss can be achieved compared to the state of the art. For similar outdoor and indoor climate conditions at 10 instead of 2 Pa pressure difference, the average ventilation rate is reduced which gives rise to better thermal comfort, although higher air velocities partly weaken this effect. When local air pollution occurs, the increased extract rate will give rise to higher pressure differences over the trickle vent, guaranteeing in this way good IAQ in the room. By preventing cross ventilation (back draft valve) an extra reduction of the ventilation heat loss and an improvement in thermal comfort occurs.

Further research in the climatic chambers will be focussed on varying inlet angles (till 90°), different outdoor temperatures and preheating effects on thermal comfort.

ACKNOWLEDGEMENT

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